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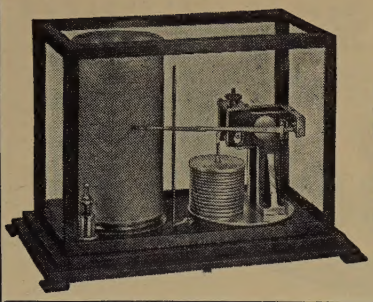

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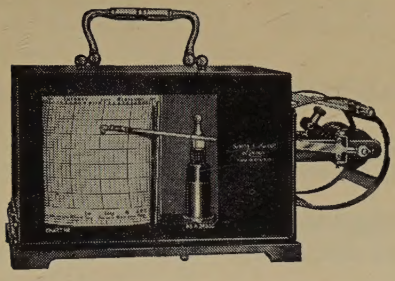

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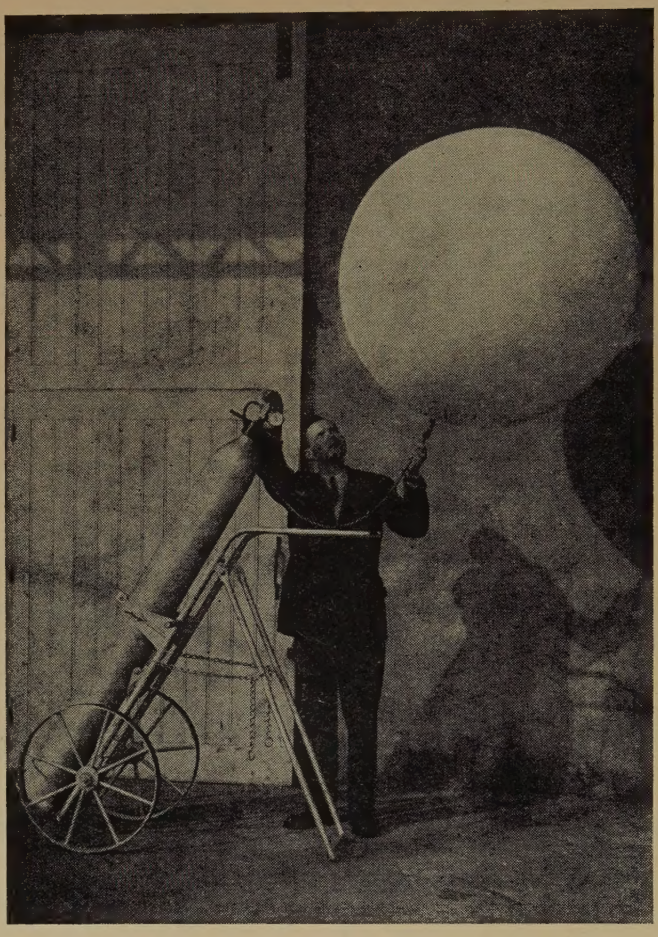

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Transfer across the earth's surface and through the air above

By P. A. SHEPPARD

Presidential Address delivered before the Royal Meteorological Society on 23 April 1958

1. Introduction

A new-comer to the subject of meteorology, browsing over its literature, particularly s dynamical and thermodynamical literature, might be excused for forming the opinion iat the theoretical meteorologist was hoping to account for the evolution of the atmosphere i terms of adiabatic transformation of a frictionless system. Perhaps the meteorologist able to make substantial progress in his study within these constricting limits. Certainly ie less complex system is worthy of study before the more complex. But we all, of course, now that we should have no weather to study and that we should not be here to study nything if the atmosphere had no heat sources or sinks and were devoid of friction.

The signs are in fact appearing that even in those fields where the adiabatic assumption as proved least restricting, as in the dynamical study of large-scale systems, models must egin to be more realistic thermodynamically, and to possess friction. Old problems, uch as the general circulation, in which heat and momentum transfer are at the heart f the matter, are also now being treated afresh. I thought therefore that it would be pportune to consider the problem of the transfer of heat, momentum and matter in the tmosphere. I shall restrict myself to transfer in the vertical but even this problem is too irge to be adequately discussed in the time available and I must ask your indulgence if deal only with some aspects which have particularly interested me or about which I eel able to say something to the point. I shall start at the earth's surface but I hope to limb well into the atmosphere before I stop.

My attitude will be unashamedly practical. The theory of transfer processes in the tmosphere is in the most rudimentary state, far more so than for example the dynamical ieory of large-scale motions (themselves a part of the transfer problem), and were I to onfine myself to well-argued theory I should have little to say. But I believe there is ow a substantial body of knowledge on transfer which can be expressed in terms con- istent with such theory as we possess, well tried in experience and therefore applicable. Man did not wait to fly until he had created a theory of flight, but, by flying encouraged ie development of theory, with consequent feedback. Meteorology is a more difficult tudy than aeronautics but we too can try our wings and expect similar results.

2. Transfer at the earth's surface

I begin my discussion with a consideration of the transfer of heat, matter (water apour, ozone, carbon dioxide, radon, etc.) and momentum across the earth's surface self. It is an obvious and important starting point, for the transfer at the lower boundary an integral quantity in that all that crosses the boundary is a complete loss or gain to ie atmospheric column above.† Elsewhere in the column it is not so much the flux of n entity as its vertical divergence which is meteorologically significant, though to be sure, is the flux itself which poses the problem of process.

† The statement requires some qualification in respect of heat.

It is then most desirable to have reliable, direct methods for the measurement of the surface fluxes, but we must admit that, as yet, we only have direct methods of acceptable accuracy for special cases. First among these (radiation apart) I would place Pasquill's (1949a) and Rider's (1954) gravimetric measurements of evaporation from relatively simple surfaces. Probably also the direct measurement of surface drag by drag plates can be made acceptably for some natural surfaces, though a recent volume (Lettau and Davidson 1957) gives one pause. The transfer of sensible heat across the surface by conduction, which is the residual of the net radiation transfer, the transfer of latent heat, the heat transmitted downwards from the surface, and the photo-chemical heat, is presumably impossible of direct measurement. Since the ocean defeats us and is likely to continue to defeat us in all three problems, I hasten to add that we do not, of course, need direct methods of measurement for all situations. Our task is rather to relate direct measurements in satisfactory conditions to simultaneous other measurements (in the air above the surface) of wider applicability. This I shall deal with below. Before passing on I would express the need for more comprehensive direct measurements of surface drag and evaporation on suitable sites so that these two surface fluxes can be more adequately related to conditions above the surface. If the components of the heat flux can be simultaneously measured with satisfactory accuracy – but this is quite a problem – well and good.

3. Fully turbulent flow in the layer of constant flux

In general the vertical flux of any entity varies with height. In the absence of advection and of special sources – of momentum, a force; of heat, a degradation of kinetic energy – conservation demands that the vertical flux derivative shall be proportional to the temporal rate of change of the corresponding property of the air. It is, however, evident by appeal to observed rates of change and otherwise that, in general, the variation in flux of heat, matter and momentum over the first few decametres of the atmosphere is at most a few per cent of the surface flux. Consequently, a measurement of flux within this layer provides for most purposes a satisfactory value of the surface flux and we may assume constancy of flux in a theoretical treatment of the problem of transfer in the layer. This simplification has greatly aided the development of the study.

The vertical flux of heat in the atmosphere is partly radiative but I shall exclude this component of the flux from consideration unless reference to the contrary is made. Its neglect is justifiable only when its divergence is negligibly small, whether the total flux is, or is not, independent of height.

In a fully turbulent flow, that is a flow in which molecular ' conduction ' is quite outweighed by bulk mixing of the fluid, the mean upward vertical flux F of an entity s, per unit mass of fluid, is given by

$$F = \overline{\rho s w}$$

where ρ is the fluid density, w the vertical component of velocity and the bar implies a spatio-temporal mean for the height z to which the symbols refer. In the layer of constant flux, mean vertical motion over a horizontal surface is necessarily very small compared with the observed eddy velocities and I shall take w in the expression for F to be the vertical eddy velocity. I shall further take ρ outside the bar, which is not to assume that density fluctuations exert no influence on transfer but that their effect is primarily evident in the w or s field. The total flux is then the eddy flux

$$F = \rho \overline{sw}$$

The measurement of the covariance of s and w (or of s and ρw, without the above approximation) thus leads to the vertical flux of s, and the method has been exploited in recent years by a number of workers for momentum, heat and water-vapour transfer. It is, however, beset with difficulties, experimental and interpretative, which I shall not go into here, but which make the correlation between the fluxes and the macroscopic

onditions difficult to achieve with any measure of confidence. The difficulties will no oubt be slowly overcome but they give point at present to the suggestion made above o exploit to the full direct methods† of measurement of surface flux.

4. The layer of constant flux with nearly neutral stability

Let me now recapitulate present knowledge of the relation of the vertical flux to the nacroscopic or mean variables in a fully turbulent layer of constant flux when the effects f buoyancy on the turbulent motion are negligibly small. It is not possible, *a priori*, o say how large a departure from an adiabatic lapse-rate is tolerable in order that the last ondition shall be satisfied but I shall return to the point later. Since fully turbulent low is to be considered, a layer of air immediately above the surface, in which molecular onduction is necessarily significant for the diffusion of heat and gaseous matter, is ex- luded from our analysis. I shall assume processes to be independent of the horizontal oordinates (quasi-homogeneity in the horizontal, with negligible advection) and of time time rates of mean conditions very small compared with time rates of eddy mixing process).

When s is the horizontal momentum per unit mass of a uni-directional flow,

$$-\frac{F}{\rho} \equiv \frac{\tau}{\rho} = -\overline{uw} \equiv u_*^2 = \text{constant} \quad . \quad . \quad . \quad (1)$$

vhere τ is the horizontal shearing stress, u is the downwind eddy velocity and u_* is called he friction velocity. Dimensional analysis then leads to an expression for the vertical radient of mean wind speed U

$$\frac{\partial U}{\partial z} = \frac{u_*}{kz} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

vhere k is a universal dimensionless constant. The origin of z is taken (not quite strictly) o be the level where $U = 0$. Integration gives the well-known logarithmic law

$$\frac{U}{u_*} = \frac{1}{k} \log \frac{z}{z_0} \ldots . \; z > z_0 \quad . \quad . \quad . \quad (3)$$

vhere z_0 is a constant of integration, reflecting the nature of the momentum-transfer rocess at the base of the fully turbulent layer. I shall be concerned only with surfaces vhich are aerodynamically rough, for which z_0, by definition, is independent of the viscosity f the air and is termed the roughness length. This does not appear to exclude any natural urface of meteorological importance. The roughness length and k, which is known for istorical reasons as von Kàrmàn's constant, are to be determined by observation. The est value of k appears to be 0·41 (Clauser 1956). If z is measured from the base of the oughness elements rather than from the level of zero mean wind which may be somewhat igher, it is necessary to introduce a zero-plane displacement d so that $z - d$ replaces z n Eq. (3). The measurement of surface drag does not involve z_0 directly for, from (3)

$$u_* = \frac{k\,(U_2 - U_1)}{\log z_2/z_1} \quad . \quad . \quad . \quad . \quad (4)$$

he subscripts 1, 2 referring to levels of observation.

The validity of (2) to (4) for the flow of air over a land surface has been successively lemonstrated by Sheppard (1947a), Pasquill (1950) and Rider (1954), and there is strong resumptive evidence for the validity of these relations over the sea also (Hay 1955; Deacon, Sheppard and Webb 1956). For a disturbed sea, the surface geometry and so z_0 are the result of interaction between wind, through surface drag, and water, under

† The determination of flux from the covariance of the fluctuations is also rightly called a direct method, but only by virtue of he existence of a layer of constant flux is it a direct method of obtaining surface flux.

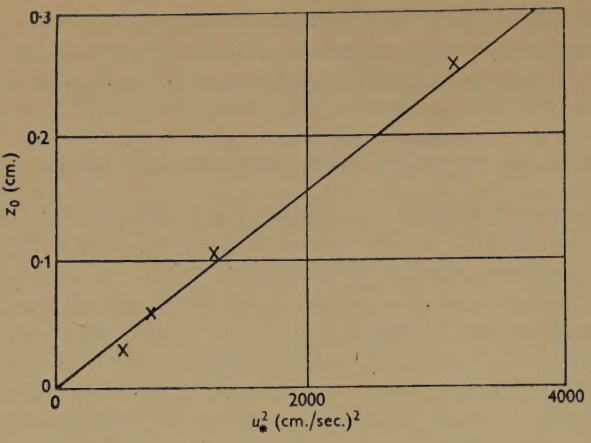

Figure 1. Variation of aerodynamic surface roughness z_0 of the sea surface with the surface stress ($\propto u_*^2$). From Ellison (1956), using Hay's (1955) data.

gravity g, which has led Charnock (1955) to propose, from dimensional analysis, a local equilibrium relation

$$z_0 = \frac{u_*^2}{ag} \qquad . \qquad . \qquad . \qquad . \qquad . \qquad (5)$$

where a is a numerical constant. It is implied that the capillarity and viscosity of the water do not affect z_0. Ellison (1956) has shown (see Fig. 1) that the relation is satisfied by Hay's data. These imply a value of a of about 13 and those of Deacon, Sheppard and Webb a value of about 20, i.e., a rather slower increase of z_0 with u_*.

If, as is conventional, the surface drag τ_0 is expressed in terms of the 'anemometer wind' U_a ($z_a \simeq 10$ m) and a dimensionless drag coefficient c, according to $\tau_0 = c\,\rho\,U_a^2$, then

$$c = \left(\frac{u_*}{U_a}\right)^2 = \left(\frac{k}{\log z_a/z_0}\right)^2 \qquad . \qquad . \qquad . \qquad . \qquad (6)$$

For common crops we find c to vary from about 0·0028 to 0·008 (u_*/U_a from 1/20 to 1/9) for a representative variation of z_0 from 0·5 cm to 10 cm or about 1/10 of the height of vegetation.

From (3), (5) and (6), the drag coefficient of the sea is related to U_a, for winds producing waves, by

$$c^{1/2} \log \frac{a\,g\,z_a}{c\,U_a^2} = k \qquad . \qquad . \qquad . \qquad . \qquad (7)$$

which, within the probable range of a, is rather well approximated by a linear relation between c and U_a for 1 m/s $< U_a <$ 20 m/s. Until more satisfactory profiles of wind have been obtained over the sea it appears that an acceptable estimate of c in near-neutral conditions may be

$$\left.\begin{aligned} c = (0{\cdot}80 + 0{\cdot}00114\,U_a)\,10^{-3} \ldots\ & U_a \text{ in cm/s} \\ & z_a = 10 \text{ m} \end{aligned}\right\} \qquad . \qquad . \qquad (8)$$

It is of interest that Francis (1951) found a linear relation between c and wind speed in experiments in a wind-wave tunnel.

Introducing now the concept of eddy viscosity K defined by $\tau/\rho = K\,\partial U/\partial z$, it follows from (2) that

$$K = k\,u_*\,z \qquad . \qquad . \qquad . \qquad . \qquad . \qquad (9)$$

The utility of the concept relates not only to momentum transfer itself – the previous relations involving τ_0 (or u_*) had no need of it – but to its application to the transfer of other entities, by assuming identity or proportionality of transfer coefficients. Momentum, unlike the entities now to be considered, is affected by pressure forces, so that there is no *priori* reason for expecting identity of transfer coefficients. But the assumption of identity can be tested in its results. These are readily seen to be, for water vapour,

$$\frac{F}{\rho} \equiv \frac{E}{\rho} = -K\frac{\partial r}{\partial z}$$

where E is the rate of evaporation and r the humidity mixing ratio, leading by substitution for K and integration between levels z_1 and z_2, to

$$E = \frac{\rho k^2 (U_2 - U_1)(r_1 - r_2)}{(\log z_2/z_1)^2} \quad . \quad . \quad . \quad (10)$$

The validity of this expression in near-neutral stability has been amply confirmed by Pasquill (1949a) and Rider (1954) using the gravimetric method for the measurement of E. Identity of eddy viscosity and diffusivity is thereby implied. For those who are unfamiliar with making profile measurements of velocity and humidity I give an isopleth diagram of E in Fig. 2 which has $U_2 - U_1$ and $r_1 - r_2$ as coordinates for $z_2/z_1 = 2$. The figure indicates the accuracy with which the wind and mixing ratio observations must be made in order to achieve any required accuracy in E.

Again, for the vertical flux of heat H,

$$\frac{F}{\rho} \equiv \frac{H}{\rho} = -K c_p \frac{\partial \theta}{\partial z}$$

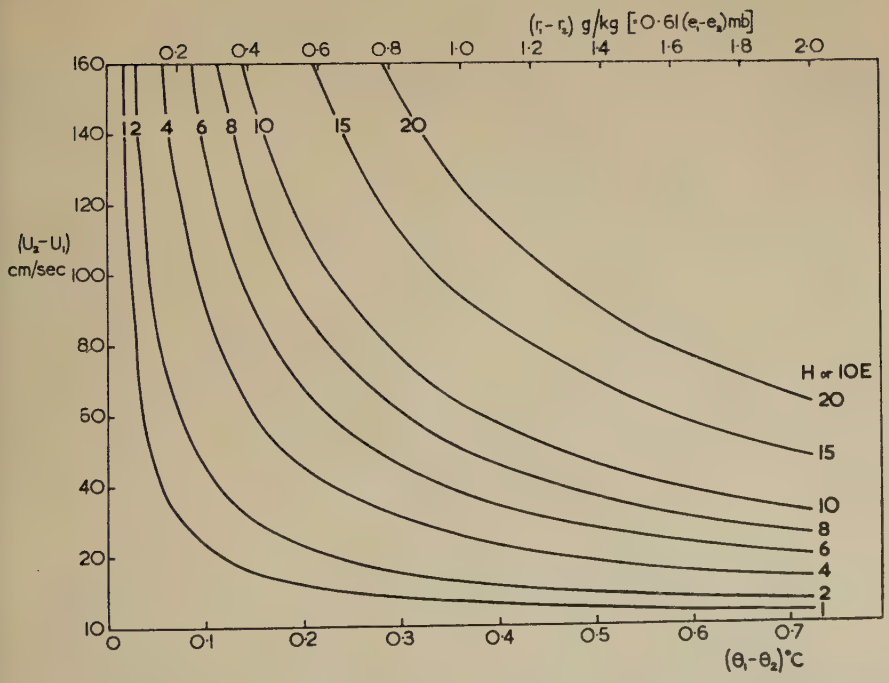

Figure 2. Isopleth diagram of rate of evaporation E (mm/hr) in terms of wind speed and mixing ratio differences $(U_2 - U_1)$, $(r_1 - r_2)$ for heights of observation z_1, z_2, with $z_2/z_1 = 2$. Near-neutral stability. The isopleths also give the heat transfer H (mw/cm^2) using the temperature difference $\theta_1 - \theta_2$ as abscissa in place of $r_1 - r_2$. Fully forced convection.

where θ is potential temperature and c_p the specific heat of air at constant pressure. Then, when the wind is sufficiently strong in relation to the lapse-rate that the latter does not affect the transfer mechanism, we obtain, as the analogy of (10)

$$H = \frac{\rho c_p k^2 (U_2 - U_1)(\theta_1 - \theta_2)}{(\log z_2/z_1)^2} \quad . \quad . \quad . \quad (11)$$

This is the equation of fully forced convection. It has not been directly tested so effectively as (10), for good enough reasons, but confirmation of (10) practically implies confirmation of (11). The problem at hand is rather to determine the limits of $(U_2 - U_1)$, $(\theta_1 - \theta_2)$ and z_2 within which the relation may be applied with confidence (see § 6). In Fig. 2, the isopleths of E become isopleths of H, from (11), when the abscissa $r_1 - r_2$ is replaced by $\theta_1 - \theta_2$ as shown.

The relations (4), (10) and (11) are important achievements for application to suitable surfaces – the sea and macroscopically uniform land – but the problem of large irregular land surfaces needs to be tackled by other methods which are not yet clearly defined. Penman (1948, 1950) has developed and exploited some of the possibilities.

An interesting application of the above treatment which seems to be emerging is the measurement of the downward flux of ozone at the earth's surface. Regener (1957) has reported the first profiles of ozone to this end. Such measurements can provide not only the strength of the ozone sink (apart from reduction by aerosol), which is of immediate concern in the ozone balance problem, but information on transfer processes generally between the stratosphere and troposphere (§ 9).

Before proceeding to the generalization of the results of this section to conditions which are significantly different from neutral stability I shall pause to consider the form which the flux relations might take when use is made of the temperature or humidity at the earth's surface itself.

5. Flux equations using surface conditions

The method just discussed for the measurement of flux demands observations at two levels in the air by refined techniques and may not be used on a synoptic basis. If one level were the surface itself large temperature and humidity differences would be available for measurement and come within the present scope of routine observation at sea (for the land, there is first a problem of defining surface conditions in terms of reproducible instrumental procedures). Unfortunately there is as yet no generally accepted relation between flux and surface-to-air differences. The theoretical problem is formidable because of the need to provide for the molecular diffusion of heat and vapour at a complex surface at which, however, molecular viscosity is of no concern. Moreover, with heat transfer, as Robinson (1950) has shown, there may be a significant divergence of radiative flux very near the surface with strong surface heating and cooling and light winds.

The climatological procedures of Jacobs (1951 and earlier), valuable as they have proved in their context, are not what is sought. An appropriate starting point for heat transfer, when molecular and eddy conduction are involved, is

$$H = -\rho c_p (\kappa + K) \frac{\partial \theta}{\partial z}$$

where κ is the molecular diffusivity for heat ($= 0{\cdot}21$ cm^2/sec for air). The problem is now to find an expression for K which is satisfactory for very small z. Sverdrup (1946), after earlier work by Montgomery (1940) and himself, chose to neglect κ and to take $K = k u_* (z + z_0)$. Integration then gives

$$H = \frac{\rho c_p k u_* (\theta_0 - \theta)}{\log \dfrac{z + z_0}{z_0}}, \quad = \frac{\rho c_p k u_* (\theta_0 - \theta)}{\log z/z_0} \text{ for } z \gg z_0$$

where $\theta = \theta_0$ at $z = 0$. My own view is that the molecular property must appear and would retain κ and take $K = k u_* z$ though this form for K is probably an oversimplification for very small z. Integration in this case yields

$$H = \frac{\rho c_p k u_* (\theta_0 - \theta)}{\log \frac{k u_* z}{\kappa}} \quad \ldots . z \geqslant \frac{\kappa}{k u_*} \qquad (12)$$

and the corresponding equation for evaporation is evidently

$$E = \frac{\rho k u_* (r_0 - r)}{\log \frac{k u_* z}{\delta}} \quad \ldots . z \geqslant \frac{\delta}{k u_*} \qquad (13)$$

where δ is the diffusivity of water vapour in air ($= 0{\cdot}25$ cm^2/sec).

These equations are for application to a rough surface for which u_* is available empirically, from (6) to (8) above ((7) or (8) above for the sea surface to which (12) and (13) are particularly directed).† Sverdrup's equation for H and the similar equation for E, give values which may be up to about 50 per cent different from those given by (12) and (13) for extreme conditions. I know of no observations of H or E over the sea which might shed light on the problem, whereas on land the surface conditions are not known. However, from (12)

$$\frac{\theta_0 - \theta_1}{\theta_1 - \theta_2} = \frac{\log \frac{k u_* z_1}{\kappa}}{\log z_2/z_1} = R \text{ say}$$

where, as before, subscripts indicate levels of measurement. A similar relation may be written for mixing ratio. We are still lacking profiles of quality over the sea but I have tested a few series of observations against these relations with the results shown in Table 1.

TABLE 1. COMPARISON OF OBSERVED AND CALCULATED SURFACE-TO-AIR AND AIR-TO-AIR TEMPERATURE AND HUMIDITY RATIOS

Observer	Element	R		z_1 (m)	z_2 (m)	Conditions
		Obs.	Calc.			
Montgomery	r	7·1	5·8	1	4	Lapse and inversion
Wust	r	5·9	6·0	1	4	Lapse
Montgomery	θ	4·2	4·9	1	5	Lapse
Wust	θ	6·2	5·2	1	5	Lapse
Johnson	θ	6·3	9·0	2	5	Lapse
Deacon *et al.*	θ	7·0	9·5	4	13	Inversion
	Mean	6·1	6·7			

References: for Montgomery and Wust, see Sheppard (1947b); for Johnson and Deacon *et al.*, see Deacon *et al.* (1956).

No great encouragement is to be taken from the moderately good agreement between computed and observed ratios shown in Table 1 for there is much spread in the observed values. Sverdrup (1946) has also found some observational support for his treatment, again with much spread in observed values.

There is clearly here an important field to explore more carefully, both over sea and land. The synoptic study of energy exchange between the sea and the air might prove particularly rewarding.

† An equation for τ_0 analogous to (12) and (13) but containing the kinematic viscosity ν would refer to the drag of a smooth surface. It would give too high a drag, implying too *high* an eddy viscosity which should rather take a form $K = k u_* z f(u_* z/\nu)$. The momentum transfer coefficient immediately above a rough surface must presumably be greater than $k u_* z$ – it cannot vanish at the surface – but its finite value at the surface is due to pressure forces which have no analogue for heat and vapour transfer. It is for this reason that I use $k u_* z$ itself for the eddy conductivity and diffusivity.

6. Constant flux layer with thermal gradient

Workers in the field of vertical transfer have long been concerned to find appropriate generalizations of Eqs. (4), (10) and (11) for a non-adiabatic lapse rate. Rossby and Montgomery (1935) made the first notable impression on the problem for a stable atmosphere and the next significant step was, I believe, taken by Deacon (1949). He found that observed wind profiles could be well represented by

$$\frac{\partial U}{\partial z} \propto z^{-\beta} \quad . \quad . \quad . \quad . \quad . \quad (14)$$

where β, a stability parameter, is < 1, $= 1$ and > 1 in stable, neutral and unstable conditions respectively, and, for a given surface, is a function of the Richardson number $\mathscr{R} \equiv \frac{g}{\theta}\frac{\partial \theta}{\partial z}\Big/\left(\frac{\partial U}{\partial z}\right)^2$. Now, in near-neutral conditions in which the logarithmic profiles (4) and (11) for U and θ are satisfied, $\mathscr{R} \propto z$, and in other conditions $\mathscr{R}$ is also likely to diminish numerically in approaching the surface. (The equation of vertical motion shows that buoyancy must have diminishing effect on the field of motion as the surface is approached). For such reasons Deacon assumed that the general wind profile must approach the adiabatic form for small z and with this as boundary condition integrated Eq. (14) to obtain

$$\frac{U}{u_*} = \frac{1}{k\,(1-\beta)}\left\{\left(\frac{z}{z_0}\right)^{1-\beta} - 1\right\} \quad . \quad . \quad . \quad (15)$$

which implies

$$K = k\,u_*\,z_0\left(\frac{z}{z_0}\right)^{\beta} \quad . \quad . \quad . \quad . \quad (16)$$

If identity of transfer coefficients is again assumed (of which, more below) expressions for the vertical flux of heat and water vapour in terms of u_*, $\theta\,(z)$ and $r\,(z)$ can be immediately deduced.

Deacon's treatment has been most useful in correlating data but it has two limitations, one purely practical, that β is difficult to measure with satisfactory accuracy, the other more fundamental, that (15) is a relation which can hardly arise from a dimensionally consistent analysis of the problem. For such an analysis we come forward to another milestone in the subject provided by Monin and Obukhov (1954).

The problem is to relate the vertical gradients of mean wind and potential temperature with the fluxes of momentum and heat – both constant over the layer concerned – and with the height and gravity. These quantities would appear to be the only possible set of concern in a quasi-steady, horizontally uniform field of fully developed turbulence. As before, we represent the momentum flux by the parameter $u_*\,(= \overline{uw}^{1/2})$, and instead of H we use $H/\rho\,c_p\,(= \overline{wT'})$ where T' is the fluctuation of temperature from the mean (cf. § 3). Gravity gives rise to the buoyancy force $\frac{g}{T}T'$ per unit mass of air, where T is the mean temperature at the level, and so it is appropriate to use g/T as the buoyancy parameter. (T varies from level to level but only by a very small fraction of itself so that g/T can be regarded as constant). For a similarity solution of the problem, any velocity, length or temperature difference entering the analysis should be expressed in terms of appropriate combinations of u_*, $H/(\rho\,c_p)$ and g/T. The only velocity from this set is u_*, the only length $u_*^3\Big/\left(\frac{g}{T}\frac{H}{\rho\,c_p}\right)$, and the only temperature $H/(\rho\,c_p\,u_*)$ and we write

$$L \equiv \frac{u_*^3}{k\,\frac{g}{T}\frac{H}{\rho\,c_p}}, \quad T_* \equiv -\frac{H}{\rho\,c_p u_*}$$

where von Kàrmàn's number k has been introduced into L for later convenience.

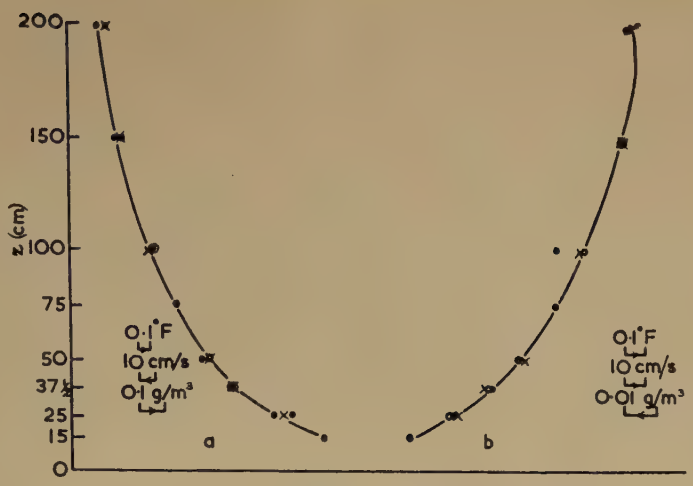

Figure 3. Examples of superposed wind, temperature and humidity profiles over grass by Rider (1954). Wind o, temperature ×, humidity ●.

In the near-neutral case we wrote (Eq. 2), on dimensional grounds,

$$\frac{z}{u_*}\frac{\partial U}{\partial z} = \text{constant (pure number)}$$

but in the non-neutral case the constant must be replaced by a non-dimensional variable involving z and therefore z/L. Thus

$$\frac{kz}{u_*}\frac{\partial U}{\partial z} = \phi_1\left(\frac{z}{L}\right) \quad . \quad . \quad . \quad . \quad . \quad (17)$$

where ϕ_1 is an undetermined function. This implies that the eddy viscosity $K_{\text{mom}} = k\,u_*\,z/\phi_1\left(\frac{z}{L}\right)$. Similarly

$$\frac{kz}{T_*}\frac{\partial \theta}{\partial z} = \phi_2\left(\frac{z}{L}\right) \quad . \quad . \quad . \quad . \quad . \quad (18)$$

where ϕ_2 is a second undetermined function. The eddy conductivity $K_H = k\,u_*\,z/\phi_2\left(\frac{z}{L}\right)$. This is as far as dimensional analysis will take us in the general case but as always it provides an appropriate framework for the analysis of observations. The analysis essentially remains for the future but some further progress has been made by Monin and Obukhov.

If the profiles of U and θ are similar ($\partial U/\partial z : \partial\theta/\partial z$ = constant) it follows from (17) and (18) that $\phi_1 \propto \phi_2$ and $K_{\text{mom}} \propto K_H$. No systematic difference between velocity and temperature profiles over the first few metres has been established to my knowledge and Rider (1954) is able to state categorically that they always have the same form between 0·15 m and 2 m. Some of Rider's individual profiles are reproduced in Fig. 3 and they speak for the high quality of his technique. I have also examined Swinbank's (1955) profiles of U and θ over the larger height range 0·5 m to 8 m (and in some cases to 32 m) and can find no systematic difference of form when grouping profiles according to the value of Richardson's number at a fixed height. (Difference of form almost certainly arises however at heights of a few tens of metres in conditions of strong surface heating (see, e.g., Frankenberger 1952)). Following Monin and Obukhov I shall in fact take $\phi_1 = \phi_2$ ($K_{\text{mom}} = K_H$) which is rather more than is implied by similarity of profiles but the subsequent analysis remains valid for ϕ_1/ϕ_2 = constant = a if θ is replaced by θ/a.

Now, as $|L| \to \infty$ ($H \to 0$), Eq. (17) must reduce to Eq. (2) so that $\phi(0) = 1$. Thus for given L, and $z \ll |L|$, $\phi(z/L) \simeq 1$ and the properties of the field for these z differ imperceptibly from those of a field in neutral equilibrium as already inferred above. This is the regime of fully forced convection (Eq. 12) and the significance of L and of z/L is apparent.

Developing ϕ as a power series,

$$\phi\left(\frac{z}{L}\right) = \phi(0) + \alpha\frac{z}{L} + \ldots . \simeq 1 + \alpha\frac{z}{L} \text{ for } z < |L|$$

where α is a pure number.† Inserting the two-term expression for ϕ in (17), integrating and choosing the constant of integration for consistency with (3), the velocity profile is

$$\frac{U}{u_*} = \frac{1}{k}\left(\log\frac{z}{z_0} + \alpha\frac{z - z_0}{L}\right) \ldots . z_0 < z < |L|$$

or

$$U_2 - U_1 = \frac{u_*}{k}\left(\log\frac{z_2}{z_1} + \alpha\frac{z_2 - z_1}{L}\right) \quad . \quad . \quad . \quad . \quad (19)$$

Similarly, from (18)

$$\theta_2 - \theta_1 = \frac{T_*}{k}\left(\log\frac{z_2}{z_1} + \alpha\frac{z_2 - z_1}{L}\right) \quad . \quad . \quad . \quad . \quad (20)$$

Then, from (19) and (20)

$$u_* = k\frac{(U_2 - U_1) - \alpha\dfrac{(z_2 - z_1)\ (\theta_1 - \theta_2)}{U_2 - U_1}\dfrac{g}{T}}{\log z_2/z_1} \quad . \quad . \quad (21)$$

and

$$H = \rho\, c_p\, u_*^2\frac{\theta_1 - \theta_2}{U_2 - U_1} \quad . \quad . \quad . \quad . \quad . \quad (22)$$

The corresponding profile for mixing ratio is

$$r_2 - r_1 = \frac{r_*}{k}\left(\log\frac{z_2}{z_1} + \alpha\frac{z_2 - z_1}{L}\right) \quad . \quad . \quad . \quad (23)$$

where $r_* = -E/(\rho\, u_*)$, and corresponding to (22)

$$E = \rho\, u_*^2\frac{r_1 - r_2}{U_2 - U_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

Thus, from (21) and (22), simultaneous observations of wind and temperature at two levels ($z_1 < z_2 < |L|$) will provide u_* and H once α is known, and from (24), additional simultaneous observations of humidity‡ at the two levels will provide E. Monin and Obukhov have analysed nearly a thousand wind and temperature profiles observed over the Steppes in a wide variety of conditions and infer α to be $-0{\cdot}6 \pm 10\%$. The inferred range of heat flux was from about 0·35 cal cm^{-2} min^{-1} (24 mw cm^{-2}) upward to 0·1 cal cm^{-2} min^{-1} (7 mw cm^{-2}) downward. Halstead (1952) had earlier shown that wind profiles observed by him and others fitted well a relation $U \propto \log z + \gamma z$ up to heights of at least 8 m, where γ depended on time of day. His interpretation of γ is not however acceptable. The same form of profile was found by Liljequist (1957) in stable conditions over a snow field, with γ a function of lapse rate and wind speed.

† Monin and Obukhov designate this universal parameter by β but in view of Deacon's prior use of β as a stability parameter it seems wise to use another symbol.

‡ Rider (1954) finds no systematic difference between the profiles of humidity and those for temperature and wind (cf. Fig. 1) but there is scatter within the uncertainties of measurement of humidity.

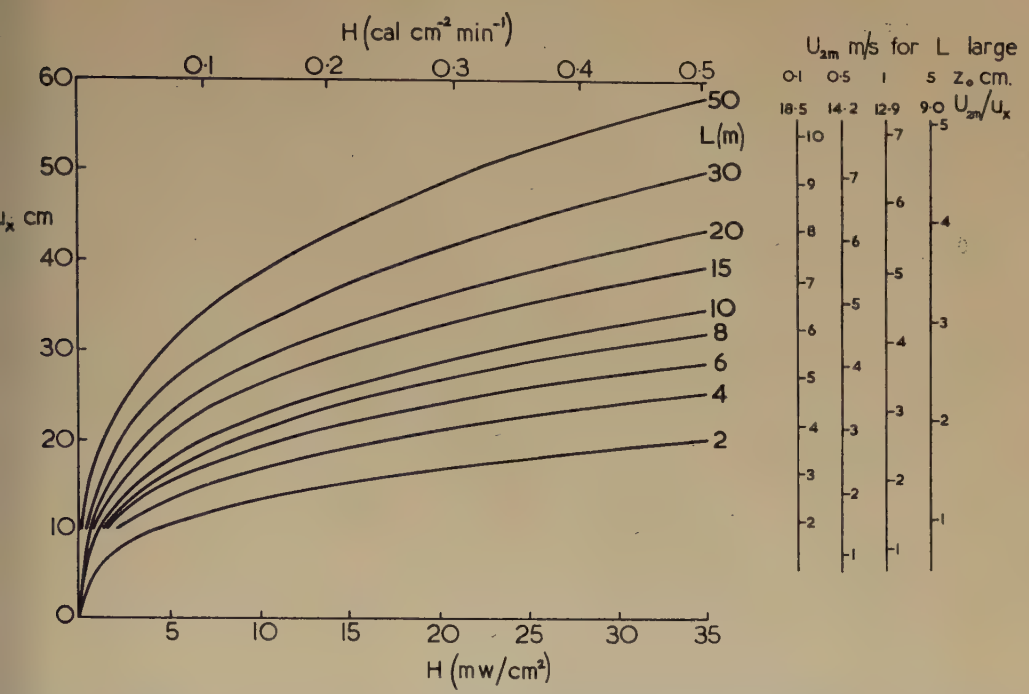

Figure 4. Isopleths of the Monin-Obukhov heat flux, stress parameter L (m) as function of u_* and H. The scales on the right show values of U_{2m} corresponding to the given u_* for $|L|$ large and various surface roughness lengths z_0.

Monin (1953) measured the heat flux by evaluation of $\rho\, c_p\, \overline{w\Gamma'}$ on 14 of the occasions referred to above and found a value of $a = K_H/K_{\text{mom}} = 0{\cdot}82$ by comparison with the heat flux determined from (21) and (22). The data are too few to make the value of this ratio reliable or to provide a check on the analysis. It is rather to be observed that Swinbank (1955) from many more observations of $\overline{\rho uw}$ and $c_p\, \overline{\rho wT'}$ inferred a ratio K_H/K_{mom}, at 1·5 m, greater than unity in unstable conditions and less than unity in stable conditions. This result is surprising if there is in fact similarity of profiles up to and beyond 1·5 m so that further careful investigation of profiles with observed fluxes is needed.

Since the validity of Eqs. (19) to (24) is restricted to heights $z < |L|$, it is of practical interest to see the values of L which are likely to be realized in the constant flux layer. These are shown in an isopleth diagram in Fig. 4 in terms of H and u_*. Values of U_{2m} corresponding to the given u_* for $|L|$ large (near-neutral conditions) are shown on the right of the diagram. It will be seen that only in very light winds and large heat fluxes is L less than a few metres so that when making application of (21) to (24) one can avoid working so near the surface as to incur the risk of unrepresentative values.

It remains to see the order of magnitude of the buoyancy ' correction ' to flux in the layer $z < |L|$. This is given by the ratio of the squares of u_* for non-neutral and neutral conditions, from (21) and (4) respectively. Isopleths of this correction, in per cent of the neutral equilibrium values of flux given by (4), (10) and (11), are shown in Fig. 5 for given $(z_2 - z_1)$ for unstable conditions (and are approximately the same but of opposite sign for stable conditions). Only in light winds – strictly with small velocity differences – and large lapse rates are the corrections really substantial. It is for this reason that I chose to deal with the near-neutral equilibrium case earlier in some detail for it is evident that the formulae for that case may be made to give good approximations to actual fluxes with appropriate heights of measurement. Pasquill (1949b) and Rider (1957) have exploited this result for evaporation, and it could always be exploited for the determination of flux from air/sea differences (§ 5), for the main part of the air/sea difference arises where buoyancy has no chance to become effective against the large shear.

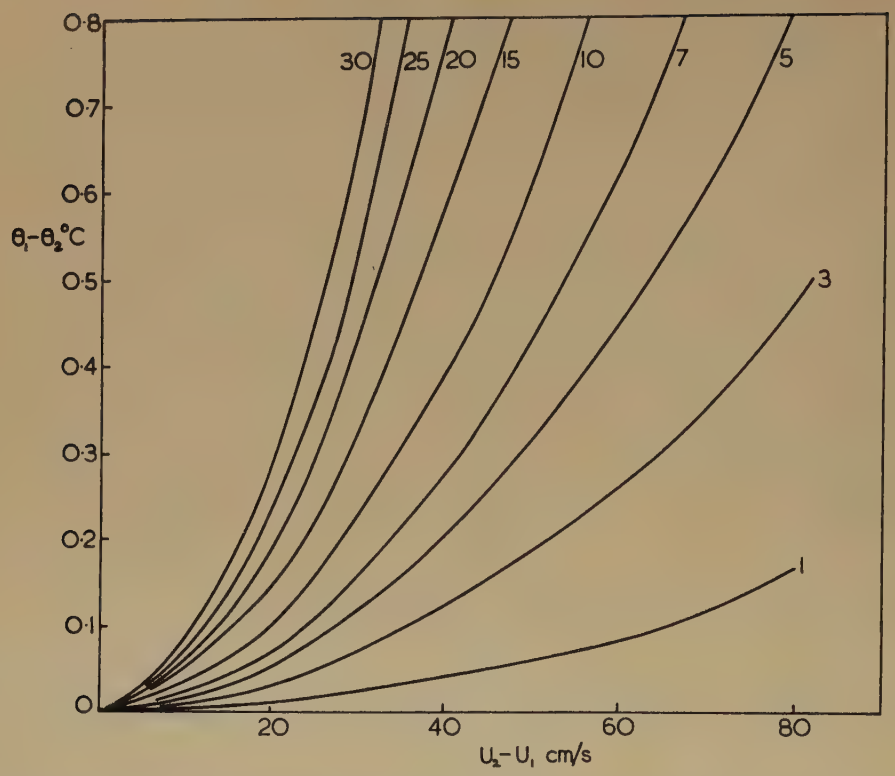

Figure 5. Isopleths of buoyancy correction to fluxes of momentum, heat and matter, in per cent of values based on formulae for neutral equilibrium (Eqs. (4), (10) and (11)), for $z_2 - z_1 = 1$ m. Superadiabatic conditions, corrections to be added. Corrections, of opposite sign, for subadiabatic conditions ($\theta_1 - \theta_2$ negative) are practically the same in the range of conditions shown. Corrections are approximately halved and doubled for $z_2 - z_1 = 0{\cdot}5$ m, 2 m respectively.

It is of interest to observe that Richardson's number $\mathscr{R}$ is given, from (17) and (18), with $\phi_1 = \phi_2$, by

$$\mathscr{R} = -\frac{z}{L}\frac{1}{\phi\,(z/L)} \qquad (25)$$

$$= -\frac{z}{L}\frac{1}{1+\alpha\dfrac{z}{L}} \ldots . z < |L| \qquad (26)$$

These are also the flux forms of Richardson's number $\left(= Hg\Big/\left(c_p\, T\tau\frac{\partial U}{\partial z}\right)\right)$ when $\phi = \phi_1$, and ϕ_2 is not involved. Thus $\mathscr{R}$ for any z is directly related to L which, being a bulk parameter for the layer of constant flux, is more apprehendable than $\mathscr{R}$. From the point of view of a description of process in a turbulent layer affected by lapse rate, what is now required is a comprehensive set of measurements of heat and momentum flux and associated profiles over a really wide range of values of z/L so as to determine the functions ϕ. A considerable challenge in technique is implied. Meanwhile it would be of interest to re-analyse Swinbank's (1955) series within the framework of the above analysis. Deacon (1955) has in fact suggested the use of a ' tribo-buoyancy ' parameter S ($= z/L$ in the present nomenclature) for the analysis of flux processes but in examining the momentum fluxes reported by Swinbank chooses to use a purely empirical expression due to Holzman to relate flux with gradient and stability.

7. Free convection

We have seen that the transfer mechanism is increasingly affected by buoyancy, sitive or negative, with increase of z and decrease of L (smaller shear, larger heat flux). though the form of the functions ϕ_1, ϕ_2 in the constant flux layer are not yet established en z becomes approximately equal to or greater than $|L|$, for unstable stratification positive) increase of z/L must lead into the regime of free convection, i.e., thermal bulence dominant. The asymptotic behaviour for large $z/|L|$ in stable conditions ust, of course, be quite different and is important in relation to the maintenance of bulence and the formation of fog.

Free convection over a horizontal surface has a considerable literature but we still ow rather little about the structure of the motion and numerical relations only begin appear. Dimensional analysis was early applied to the problem and Batchelor (1954), a Symons Memorial lecture, made a critical appreciation of this treatment which I all not repeat. In general the heat flux varies with height but if the state is quasi-steady, en it may readily be shown, on dimensional grounds, that

$$H = C\rho c_p \left(\frac{gz}{T}\right)^{1/2} (\theta_r - \theta)^{3/2} = C'\rho c_p \left(\frac{g}{T}\right)^{1/2} \left(\frac{\partial\theta}{\partial z}\right)^{3/2} z^2 \quad . \quad . \quad (27)$$

here C, C' are numerical constants and θ_r is the potential temperature at a reference vel which is the origin of z and is the level, presumably at a height above surface comrable with L, at which free convection becomes established. Further

$$\sigma_w (\equiv \overline{w^2}^{1/2}) \propto \left(\frac{H g z}{\rho c_p T}\right)^{1/3} \quad \text{or} \quad \propto \left(\frac{g}{T}\frac{\partial\theta}{\partial z}\right)^{1/2} z$$

d $$\sigma_T (\equiv \overline{T'^2}^{1/2}) \propto \left(\frac{H}{\rho c_p}\right)^{2/3} \left(\frac{gz}{T}\right)^{-1/3} \quad \text{or} \quad \propto z\frac{\partial\theta}{\partial z}$$

nce H may vary with height in the above relations, the height variation of $\partial\theta/\partial z$, , and σ_T is not prescribed. Within the layer of constant flux however it immediately llows that $\partial\theta/\partial z \propto z^{-4/3}$, $\sigma_w \propto z^{1/3}$, $\sigma_T \propto z^{-1/3}$ whereas the corresponding variations the other extreme of fully forced convection are as z^{-1}, z^0, z^0 respectively.

The precision with which temperature profiles have been observed at some distance om the surface but in the constant flux layer has been generally too poor to allow the pse rate to be used as a criterion of free convection but Priestley (1954) finds some idence in the records of the $z^{-4/3}$relation at greater heights and stronger heat fluxes. do not, however, think that the evidence from $\partial\theta/\partial z$ or σ_w, σ_T is yet sufficient to specify e conditions under which free convection becomes established.

Priestley (1955 and 1956) has proposed from an analysis of observations which ere made by his Melbourne group that the value of C' in (27) lies between 0·8 and 1·0 d that free convection may be regarded as supplanting fully forced convection rather ddenly at $-\mathscr{R} \simeq 0{\cdot}03$. In other words, the heat flux is independent of $\mathscr{R}$ for $-\mathscr{R}$ 0·03, or from (25), for $z/L > 0{\cdot}03$. I think more evidence is needed before accepting sudden transition at such a low value of z/L.

The eddy conductivity K_H in free convection in the layer of constant flux is given y (27), with H constant, as

$$K_H = C'^{2/3} \left(\frac{g}{T}\frac{H}{\rho c_p}\right)^{1/3} z^{4/3}$$

ut the corresponding eddy viscosity has not been established, nor has any convincing gument been advanced that it should differ from the eddy conductivity. Observations owever point rather strongly to $K_H/K_{\text{mom}} > 1$ in this regime (Frankenberger 1952; winbank 1955). The eddy diffusivity is unlikely to be very different from K_H, which om the above expression with $C' = 1$, $H = 20$ mw/cm^2, $z = 50$ m, is 3×10^5 cm^2/sec.

Various models have been proposed to describe the structure of free convectio including finite horizontal sheets (Sutton 1948), bubbles with diffuse wakes (Scorer a Ludlam 1953), and plumes elongated along the wind (Priestley 1956). Such models a valuable as guides to observation, and Priestley has inferred an order for $\mathscr{R}$ at whi free convection should become established. But it is not clear to me that they have y advanced the quantitative problem of flux estimation beyond the point reached by dime sional analysis and I shall not discuss them further here.

8. Transfer processes in the troposphere

I shall now turn attention shortly to transfer processes at levels in the troposphe where the motions are unlikely to be directly affected by the underlying boundary. A indirect effect of the lower boundary will in general be present, e.g., cumuliform cloud due to heat transfer from the boundary, but it may be expressed by prescribing the flu of an entity concerned at, say, the top of the constant flux layer or some higher level which boundary constraints on the motion practically disappear. The transfer process in the layer concerned will then adjust themselves to the bulk structure of the layer wind velocity, temperature and humidity as a function of height – and to the flux throug the base of the layer.

We know in fact rather little about vertical transfer in this layer, though we ma observe cumuliform clouds, the rain which they and larger cloud systems deposit, an we may compute the upward flux of radiant heat. Interpretation of observations in th free troposphere is of course made much more difficult than in the surface layer by adve tive processes and by large-scale ascent and descent, and I can hardly nibble at the prob lems here.

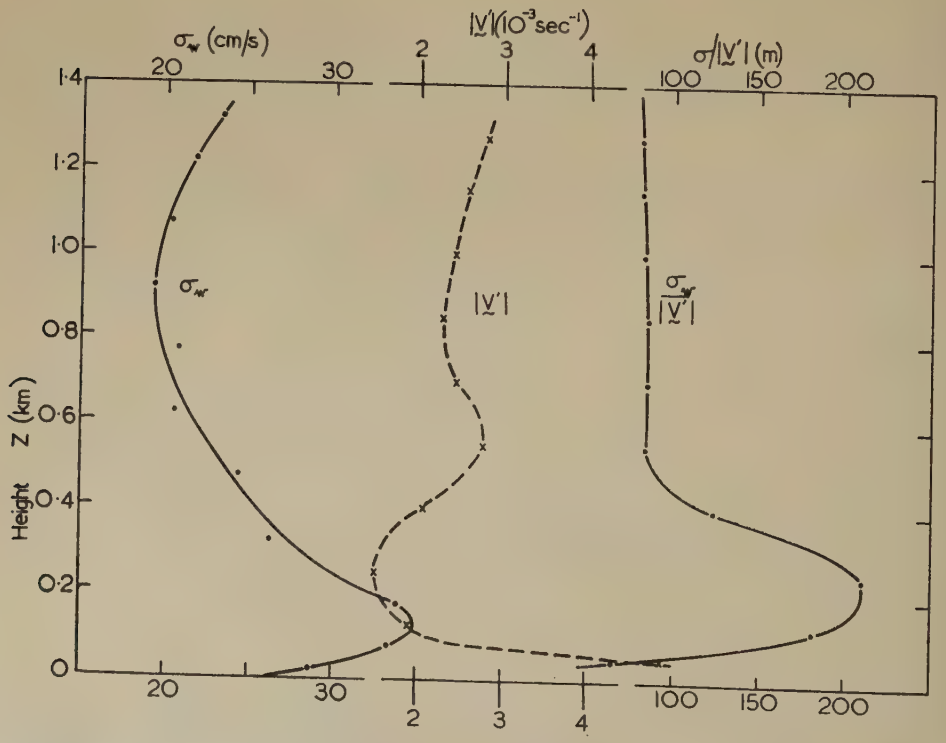

Figure 6. Balloon observations of vertical motion σ_w ($\equiv \overline{w^2}^{1/2}$) and shear of vector mean wind $|\mathbf{V}'|$ ($\equiv |\Delta\mathbf{V}|/\Delta z$ over 50 m layers in the bottom 1·5 km of the Trades on 15 days in Spring 1953. The curve of $\sigma_w/|\mathbf{V}'|$ is als shown. Balloons released from upwind side of small island (Anegada) or from boat to windward of island

Heat transfer and vertical motion in convection

Regarding the vertical flux of heat in a cloud-free layer in relation to the thermal gradient, it is my impression, supported by some analysis (e.g. Sheppard 1947b, Wilkins 1954, Lettau and Davidson 1957) that the lapse-rate is often slightly sub-adiabatic above 100 m even when strong convection is occurring (and often giving rise to cumulus at much higher levels). There is scope for further study of such a layer or of a laboratory model of penetrative convection in stably stratified fluid. An analysis of observations by Charnock, Francis and Sheppard (1956) of small-scale vertical motion in the first 1·5 km of the ocean Trades is of interest in this connection. Fig. 6 shows σ_w and the associated vertical shear $|\mathbf{V}'|$ ($\equiv |\Delta\mathbf{V}|/\Delta z$) of mean vector wind $\mathbf{V}$ in this layer which was unstable at its base and bred cumulus near its top but was slightly stable (Richardson number probably about 20) over much of its depth. The length given by $\sigma_w/|\mathbf{V}'|$ is also shown and is seen to be constant ($\simeq$ 80 m) for $z > 400$ m. Does then shear turbulence play a significant role between the lower and upper levels at which buoyancy has strong effect? Such turbulence (K of order 20 cm/s $\times$ 80 m $= 10^5$ cm^2/s) would, on its own, transfer heat downwards over the sub-adiabatic layer whereas the net flux must presumably be upward from surface to cloud base and above. The field of T' would be necessary to follow up the mechanism involved. A recent theoretical treatment by Smith (1957) of convection-diffusion processes below an inversion, in which a pollutant emitted at ground level is inferred to have a secondary maximum of concentration at the top of the convective layer, may well be relevant to the heat transport and temperature distribution in such a layer.

I have also made an analysis of σ_w for $0 < z < 1{\cdot}2$ km with strong surface heating, from smoke-puff data of the Great Plains project reported by Lettau and Davidson (1957). It shows (see Fig. 7) stronger, as expected, but similarly varying vertical motions compared with those of Fig. 6, shear of the same order, and slightly stable lapse rates above 100 m. The variation of $\sigma_w/|\mathbf{V}'|$ with height and its relation to $\mathscr{R}(z)$ suggests no control of σ_w by shear in this case, which is probably one of much stronger upward flux of heat.

A crude analysis of the Trade wind data has been made to indicate the relation of scale to intensity of the vertical motions present over the layer investigated and is shown

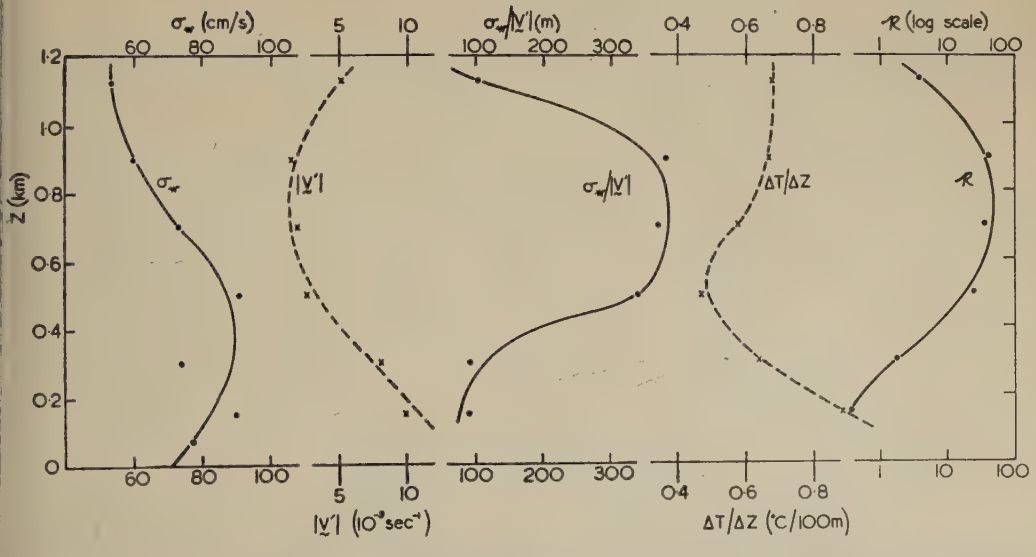

Figure 7. Observations of vertical motion σ_w (from smoke puffs) and shear of vector mean wind $|\mathbf{V}'|$ (from puffs and balloons) at O'Neill, Nebraska, between 08 and 16 LMT on 6 clear days in August, September 1953. Curves of $\sigma_w/|\mathbf{V}'|$, $\Delta T/\Delta z$ and $R\left(=\frac{g}{\theta}\frac{\Delta\theta}{\Delta z}\Big/|\mathbf{V}'|^2\right)$ as function of height also shown.

in Fig. 8. The diagram is not to be read as evidence for or against any of the convective models referred to above but it shows that maximum vertical velocity is associated with elements of order 400 m in vertical extent, a figure which theory should provide and show to be consistent with the 80 m provided by $\sigma_w/|\mathbf{V}'|$. The maximum vertical velocity is generally greater and more peaked for the rising than for the descending air, as might be expected.

In the levels at which condensation products occur the convection process is further complicated by phase changes of water, from vapour to condensate *and the reverse*, with associated changes of the thermal field, and no quantitative treatment of the transfer process engendered by cloud convection yet appears. I believe the current research of Ludlam and others on cumulus structure will lead to better understanding in due course.

Momentum transfer in the troposphere

The classical picture of the momentum transfer associated with the Ekman-Taylor spiral of a barotropic boundary layer has some relevance to flow over rough land surfaces but is quite inadequate to describe the characteristic features of the baroclinic turbulent atmosphere, particularly over the less rough ocean surface. I believe that, as a result of work with my colleagues in the westerlies and Trades, and of the work of Riehl, Yeh, Malkus and La Seur (1951) and Palmén (1955) on the Trades, the broad pattern of vertical transfer of zonal momentum begins to emerge but that several uncertainties remain.

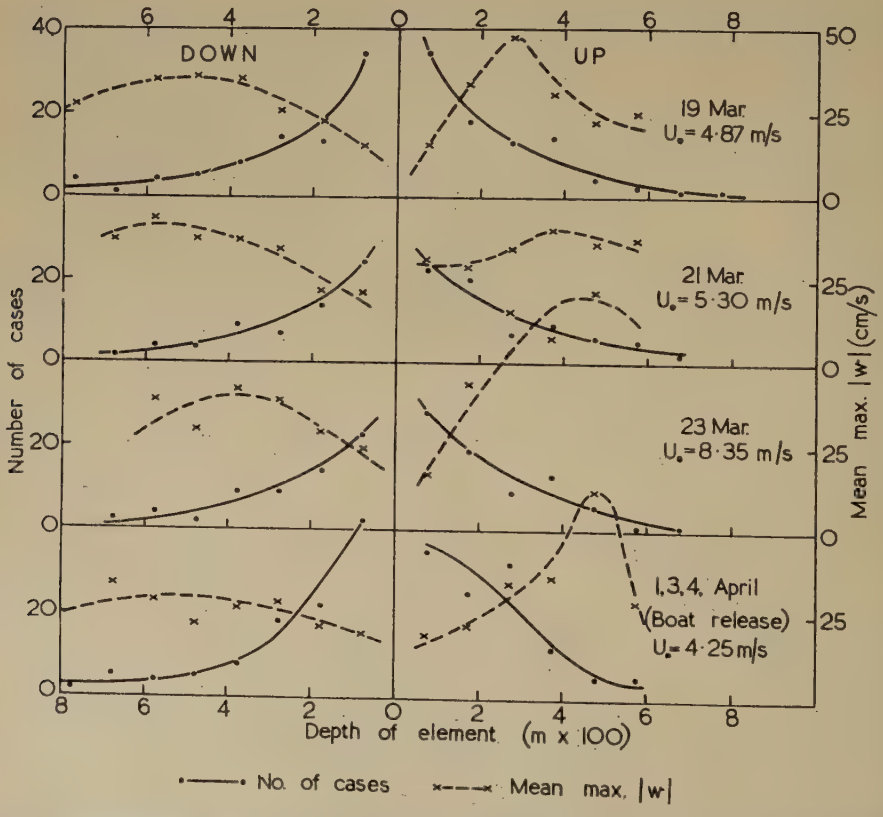

Figure 8. Frequencies and mean maximum vertical velocities, up and down, of vertically moving elements of different depths in the bottom 1·5 km of Trade wind air on 6 days in Spring 1953. U_0 = surface wind. Depth of element defined by vertical distance traversed by balloon without change of sign of vertical velocity w of air.

In the westerlies, where zonal shear is in the same sense throughout the troposphere, hermal turbulence provides a downward flux of westerly momentum above the surface ayer which, though decreasing with height, is probably comparable with the surface lrag over a substantial depth of troposphere. In the Trades, where zonal shear reverses ts sense at a few hundred metres height, there is a decreasing upward flux of westerly nomentum from the surface to the level of maximum easterly wind and an increasing lownward flux, again from thermal turbulence, for some distance above this level. The ower branches of the direct tropical and indirect extra-tropical meridional circulations reate and destroy westerly momentum respectively so as to preserve a balance with the ields of divergence of vertical flux in each zone. The oppositely directed upper branches of the meridional circulations, prescribed by continuity, provide a balance with the divergence and convergence of *meridional* flux of zonal momentum in the upper troposphere. According to this picture, the large-scale disturbances of the troposphere are not called on o effect any significant net vertical transfer of zonal momentum, which may or may not be true. Theory is not conclusive on the point and it is obviously difficult to infer the arge-scale flux from observations.

An analysis which I have made of Ocean Weather Ship winds in relation to weather s instructive for the vertical transfer problem in the westerlies. Fig. 9 shows the mean zonal (U) and meridional (V) winds at 850, 700, 500 and 400 mb for three winters for:

(1) showers or large cumulus (38 per cent of occasions);

(2) steady or intermittent precipitation (10 per cent);

(3) no precipitation and no large cumulus (52 per cent);

at 52·5°N, 20°W. The absolute values of the vector shear $|\mathbf{V}'|$ are also shown for the three classes. It is reassuring that the meridional motions are well differentiated in the

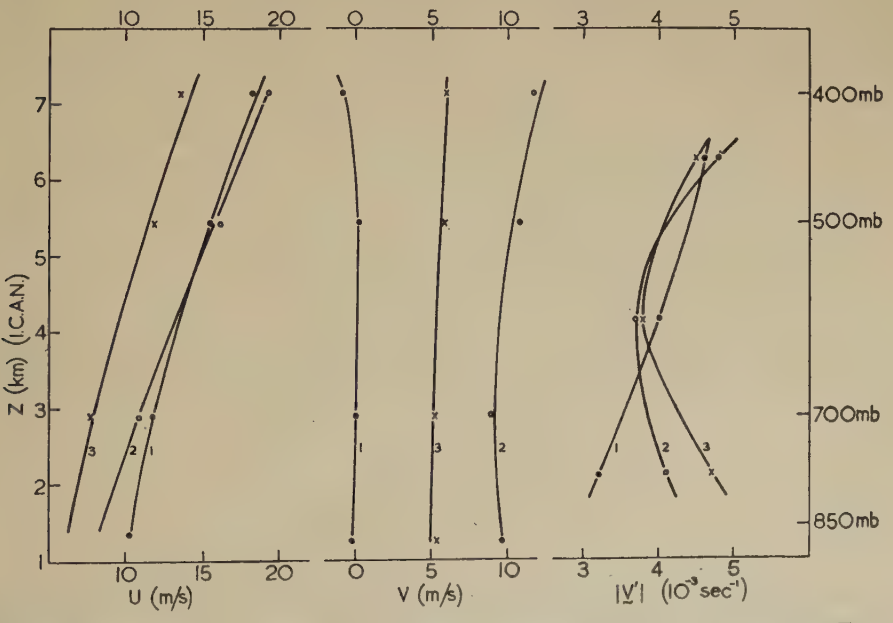

Figure 9. Radar winds from O.W.S. 52·5°N, 20°W for three winters (J-F 1955, D-F 1955/56, D-F 1956/57) for weather classes 1, 2, 3 (see text).

U = mean westerly component
V = mean southerly component
$|\mathbf{V}'|$ = mean vector shear.

expected sense. It will be seen that the zonal shear is of the same order for each class but somewhat greater for class (2) than for either class (1) or (3). Thus there is appreciable shear on which thermal turbulence may operate in class (1) and taking $\partial U/\partial z = 1{\cdot}5 \times 10^{-3}$ sec^{-1}, $K = 10^6$ cm^2/sec for this class, with ρ (700 mb) $= 9 \times 10^{-4}$ g/cm^3, we obtain a downward transfer of zonal momentum of 1·3 dyne/cm^2 at that level and a considerably greater total stress ($|\mathbf{V}'| > \partial U/\partial z$). Class (1) being present on 38 per cent of occasions, the mean zonal stress excluding all other motions, is 0·5 dyne/cm^2 for the level. This is the same order as the surface drag, but my estimate of K could of course be incorrect. The transfer by the mean vertical motion in classes (2) and (3) cannot be assessed, but the low relative incidence of class (2) will offset the presumably greater upward velocities of this class compared with the downward velocities of class (3).

I am hopeful that more quantitative information on the vertical flux of momentum throughout the troposphere (and, if present, in the stratosphere) will come from the exploitation of radar-balloon techniques initiated by Scrase (1954), but using automatic-follow radar.

9. Trace elements in the study of vertical transfer; exchange between stratosphere and troposphere

We know from the structure and incidence of convective and frontal cloud and from the properties of subsided air that matter is rather readily diffused throughout the depth of the troposphere. We know too from the evaporation – precipitation cycle and from the amount of water vapour in a vertical column that the mean life of water vapour in the troposphere is of the order of 10 days. Any other matter having its source and sink at the earth's surface, e.g., salt nuclei, radon and its decay products, will have a similar mean life if it is washed out by precipitation. The mean tropospheric life of matter, e.g. ozone, which enters the troposphere from the stratosphere and is captured or destroyed at the surface should be of the same order, though it will be longer if not in particulate form or if insoluble in water. Stewart, Crooks and Fisher (1957) have shown that the fall-out of material which may be captured by rain far exceeds the dry-deposition rate.

Knowledge of the rate at which matter may be transferred from the troposphere to the stratosphere, or the reverse, or from one level to another of the stratosphere is, by contrast, poor. Yet this has become a matter of great concern in the 'atomic' age. I do not have space to discuss the general fall-out problem in detail but one or two aspects will be alluded to. Thus, precipitation sampling in the last few years (Libby 1956, Stewart *et al.* 1957) has shown that Sr^{90}, created at levels of about 20 to 30 km by thermo-nuclear explosions, has a mean life in the stratosphere of about 10 years. This sounds almost like an absence of vertical diffusion but using the well-known Fickian relation $z^2 = 4\,K\,t$ for the height interval z over which diffusion is effective in time t, one finds a K of order 10^4 cm^2/sec. The Fickian relation may not be suitable because the transport is probably carried out largely by the slow large-scale vertical motions of the stratosphere (and possibly to some extent by gravity) but the order of magnitude of K gives another impression than the half-life of the diffusion rate. Measurements now made of the concentration profiles of Sr^{90} and Cs^{137} (nuclear half-lives of 28 and 33 years respectively) in the lower stratosphere (see Stewart *et al.* (1957) and *Annals of the International Geophysical Year*, Pt. V) merit examination in relation to the rate at which these isotopes are precipitated on the earth's surface. The study both of stratospheric diffusion and of the mechanism of transfer from stratosphere to troposphere should profit thereby. Regarding the latter process, it is commonly suggested that the break in the tropopause at the jet stream provides the main avenue for entry to the troposphere but I know of no data in direct support of the idea. Stewart *et al.* have, however, found that the deposition rate of Sr^{90} is considerably lower in tropical than in extra-tropical latitudes.

If thermonuclear explosions were outlawed tomorrow the large stratospheric reservoir Sr^{90} and Cs^{137} could provide meteorological data for many years. But nature provides with a steady source aloft of radio-isotopes from the interaction of cosmic rays with nospheric gases and I shall conclude by referring to their meteorological exploitation suggested by Lal, Malhotra and Peters (1957). These authors have computed the rates production of a number of isotopes of various half-life as a function of latitude and ight and they find that about 30 per cent of the total of each is produced in the tropos- ere. Their average tropospheric production rate of Be^7 (half-life 53 days) is confirmed the average deposition rate of Be^7 in rainfall in three latitudes, allowance being made r radioactive decay. They also find agreement between the average global production te of Be^{10} (half-life $2{\cdot}7 \times 10^6$ yr) and its deposition rate in oceanic sediment. Confidence ving thus been established in their methods, the authors go on to propose the measure- ent of isotope *ratios* in *individual* rains as a potentially powerful tool in establishing e past radiation history of the air mass from which the rain falls, for the isotope ratio epends only on this history. They have prepared hypothetical case histories of air in lation to the ratio of Be^7 to P^{32} (half-life 14·3 days) which show interesting possibilities, r example, of measuring the time since the air giving the rain last left the stratosphere was last rained out in the troposphere. Our current methods of synoptic analysis are oderately well adapted to studying the horizontal motion of the air but they are not rticularly suited to the study of vertical transfer. It will therefore be interesting to e whether the radio-isotope technique is able to make a substantial contribution to the tter field.

10. Conclusion

I have said practically nothing about the radiative transfer of heat in the vertical, hich is a subject in itself. Here I have the impression that current methods of obtaining ne flux and its divergence by one of the several semi-empirical radiation diagrams are apable of providing useful results in the troposphere but are questionable in the stratos- here. Present research is likely, I believe, to lead to much improved methods for both yers in the near future.

The relations and methods I have surveyed for obtaining fluxes in the constant-flux yer are now moderately well established and thoroughly quantitative. It may well be nat their form is not such as to make them readily applicable to the whole range of pro- lems in which they are of concern but there is something to start with.

I have necessarily been rather vague about transfer in the body of the troposphere, artly because the processes are as yet poorly explored and, as a reflection of this condition, ecause the problems themselves are not yet well-defined. Whereas, for the surface yer, the synoptic situation as such does not dictate the attitude of mind, the transfer roblems of higher levels will almost necessarily be stated in terms of the large-scale ow pattern. Problems of transfer across the tropopause and in the stratosphere will resumably demand a similar attitude and I hope I have been able to show that progress n this field is already evident and is likely to continue.

Acknowledgment

I have drawn on the work of many meteorologists for this address, some with whom ractically my only contact has been the printed word. But I have enjoyed discussion ith a majority of those whom I have quoted and active collaboration with not a few. t is a pleasure to acknowledge the stimulation of these contacts. I would specially thank he small pioneer group at Porton of the middle and late thirties and the students and taff of the post-war period at Imperial College who have helped to make the exploration f atmospheric transfer such an enjoyable and I hope profitable exercise.

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Sources and sinks of radiative energy from 30 to 90 km

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SUMMARY

The absorption of solar radiation and the exchange of long-wave terrestrial radiation are computed for the 30 to 90 km region for all latitudes using the climatological mean temperatures given by Murgatroyd (1957). Over most of the earth's surface (approximately 30° in the winter hemisphere to 60° in the summer hemisphere) there is a close approach to radiative equilibrium at all the levels considered. In the polar regions, however, there is a significant departure from radiative equilibrium with excess heating during the summer and excess cooling during the winter.

1. INTRODUCTION

The normal approach to a dynamical theory of the general circulation takes as its starting point the positions and magnitudes of the non-adiabatic sources and sinks of heat, and for this reason we present an attempt to compute the radiative sources and sinks between 30 and 90 km for the mean conditions at each latitude. We do not claim great accuracy for these computations and they are certain to be superseded in the near future. However, the reasonable nature of the final overall picture and an intuitive judgment based upon experience prompts us to claim that we are presenting a sufficiently accurate picture to merit the attention of dynamical workers.

We have neglected the effect on the radiative balance of both water vapour and dust. The latter has been considered by Woolley (1947) and Rakipova (1947), but there are no substantial data, and we shall show that there is a close approach to radiative balance for the gaseous components which are considered, without appealing to less certain factors.

The omission of water vapour has been justified by other workers (Karandikar 1946, Craig 1951) for reasons which are apparent from Table 1. The effect of a band will depend mainly upon its strength, the concentration of the gas and the nearness of the band to the maximum of the Planck curve at terrestrial temperatures. Band strengths vary little between fundamental bands. Carbon dioxide is always, and ozone sometimes present in greater concentrations than water vapour, and their bands (at 15 μ and 9·6 μ respectively) are nearer to the maximum of the Planck curve at 250°K than those of water vapour (at 6·3 μ and > 30 μ, see Goody and Robinson 1951), so it is reasonable to neglect the effect of water vapour in this particular region of the atmosphere.

TABLE 1. PROPORTIONS BY VOLUME OF IMPORTANT POLYATOMIC GASES IN THE STRATOSPHERE

Gas	Water vapour*	Carbon dioxide†	Ozone‡	
			30 km	90 km
Proportion	app. 2×10^{-6}	$2{\cdot}4 \times 10^{-4}$	4×10^{-5}	2×10^{-7}

* See Murgatroyd, Goldsmith and Hollings (1955).

† The only accurate series of measurements of carbon dioxide in the stratosphere is that of Glueckauf (1944) whose mean value was $2{\cdot}5 \times 10^{-4}$. The figure in the above table was adopted erroneously but differs insignificantly from Glueckauf's value.

‡ See Goody (1954).

These computations were undertaken at this particular time for two reasons. Firstly because the rocket observations on oxygen and ozone concentrations and on the solar ultra-violet spectrum have greatly increased the accuracy of solar absorption computations. Secondly, because we were fortunate enough to obtain details of a computing scheme worked out by Mr. A. R. Curtis for the most important constituent – carbon dioxide. We also used Curtis's scheme to justify an interpolation procedure which could be used with the results of Plass (1956) on ozone.

For the part of the atmosphere under consideration it is likely that the radiative sources and sinks discussed here are the only important non-adiabatic sources of energy. Stratospheric clouds are rare enough for their presence to be ignored and consequently latent heat of condensation should be of little importance. The recombination of atomic to molecular oxygen could be important from 90 km upwards, and this is one of the many reasons why computations were not carried beyond this altitude.

2. Data used

The concentrations of air, oxygen and ozone molecules used in the computations of solar heating have been given in detail by Murgatroyd (1957, Table 1, p. 419). The molecular oxygen densities were taken from Nicolet and Mange (1954) and are consistent with rocket observations; they are, however, not likely to be very accurate and the oxygen heating near 90 km is consequently uncertain. Air densities follow the Rocket Panel (1952), and the ozone densities are a combination of photochemical theory and rocket observations (Bates and Witherspoon 1952; Nicolet and Mange 1954; Johnson, Purcell, Tousey and Watanabe 1952). Theoretical work (Craig 1950) has shown that except near 30 km the ozone concentration should not depend to any important degree on the zenith angle. Thus when the sun shines, regardless of latitude, the adopted ozone concentrations should be applicable.

There is still some uncertainty about the intensity of the solar ultra-violet radiation and also about the absorption coefficients of oxygen and, to a lesser extent, ozone. When these computations were started we could see little reason to disagree with the estimates of Craig (1950, Table B1), and these have been used throughout this paper.

For computing long-wave radiative heating the summer and winter temperatures of Murgatroyd (1957) were used. The carbon dioxide concentration was assumed to be $2{\cdot}4 \times 10^{-4}$ parts by volume at all levels (see Table 1), although this may not be true above 90 km, and the results at the highest levels are therefore in doubt. Other data required for carbon dioxide are a line width of $0{\cdot}064$ cm^{-1} at one atmosphere pressure (Kaplan and Eggers 1956) and a histogram of line strengths in the 15 μ and associated bands, which was kindly supplied to us by Dr. L. D. Kaplan. The method of computation requires that the line intensities be represented by the sum of a series of exponential distributions

$$N(k) = \frac{1}{\sigma} e^{-k/\sigma} \qquad (1)$$

where

$N(k)\,dk$ = the fraction of lines with intensities between k and $k + dk$,

σ = the mean line intensity.

It was found that Dr. Kaplan's data could with satisfactory accuracy be simulated by the sum of two distributions of this nature, which we will call the ' strong line distribution ' ($\sigma_s = 1{\cdot}02 \times 10^3$ (wave number) gm^{-1} cm^2 with 108 lines), and the ' weak line distribution ' ($\sigma_w = 36$ (wave number) gm^{-1} cm^2 with 372 lines) respectively.

The concentrations and coefficients for the long-wave transfer in the 9·6 μ ozone band e automatically incorporated through the use of Plass's computations. Unfortunately, ass makes use of Summerfield's absorption data (1941) which disagree greatly with e more recent and precise work of Walshaw (1957). Although the ozone distribution uses is almost the same as that used by us, it is only applicable during the day-time ien the sun is shining. Recombination of atomic oxygen can lead to greater night-time ncentrations at high levels. Combined with the criticism which one of us has made of ass's methods (Plass 1957), these factors make the ozone cooling rates the most uncertain ature of this paper. Fortunately, the ozone cooling is rarely more than one-third the rbon dioxide cooling.

3. Solar absorption

The usual equations for a stratified atmosphere (Goody 1954, p. 148) were used in a fferential form and the integrations solved numerically for air masses 1, $\pi/3$, 4/3, $\pi/2$, π, 4, 2π, and 20, a series of convenient values which were found to be close enough to terpolate for required zenith angles. Results for computations at zenith angles 20°, °, 60° and 80° between 30 and 100 km have been given by Murgatroyd (1957, Fig. 1, 420).

There are two regions of rapid heating, the lower between 45 and 55 km being mainly ue to the Hartley band of ozone, while the upper, above 90 km, is due to molecular ygen.

The solar zenith angle was computed for the 21st day of each month, for each 10° latitude and for each hour throughout the day, graphical integrations being made over ch day. In computing zenith angles the altitude of the level was taken into account ut the change of solar distance through the year was neglected. The results are shown Figure 1.

TABLE 2. Comparison of the results of Pressmann (1954, Figs. 13 and 19, pp. 494, 495) with the solar heating given in this paper (°K day^{-1})

		June				December			
eight km)	Latitude	70°	50°	30°	10°	10°	30°	50°	70°
30	This paper	3·2	2·8	2·5	2·1	1·8	1·4	1·0	< 1·0
	This paper – Pressmann	− 3·2	− 2·2	− 1·6	− 1·3	− 1·0	− 0·9	− 0·6	0·0
35	This paper	4·2	4·0	4·0	3·6	2·8	2·0	0·9	< 1·0
	This paper – Pressmann	− 4·6	− 2·9	− 1·9	− 1·3	− 1·1	− 1·4	− 1·6	0·0
40	This paper	8·5	7·5	7·0	7·0	5·0	2·9	1·5	< 1·0
	This paper – Pressmann	− 0·1	− 0·5	− 0·5	+ 0·6	− 0·3	− 1·4	0·0	0·0
45	This paper	12·5	10·6	10·2	9·2	7·8	5·2	2·2	< 1·0
	This paper – Pressmann	+ 2·1	+ 1·2	+ 1·8	+ 2·9	+ 3·6	+ 2·1	+ 1·2	0·0
50	This paper	15·0	11·2	10·0	8·8	8·2	6·2	2·7	< 1·0
	This paper – Pressmann	+ 8·3	+ 4·9	+ 4·4	+ 5·1	+ 5·6	+ 4·7	+ 1·8	0·0
55	This paper	11·0	8·0	7·0	6·4	5·8	4·4	2·5	< 1·0
	This paper – Pressmann	+ 5·7	+ 3·4	+ 3·7	+ 3·4	+ 3·2	+ 2·4	+ 1·4	0·0
60	This paper	7·0	5·2	4·4	4·1	3·8	2·8	1·8	< 1·0
	This paper – Pressmann	–	− 0·3	− 0·5	− 0·3	+ 0·1	+ 0·3	+ 0·2	0·0

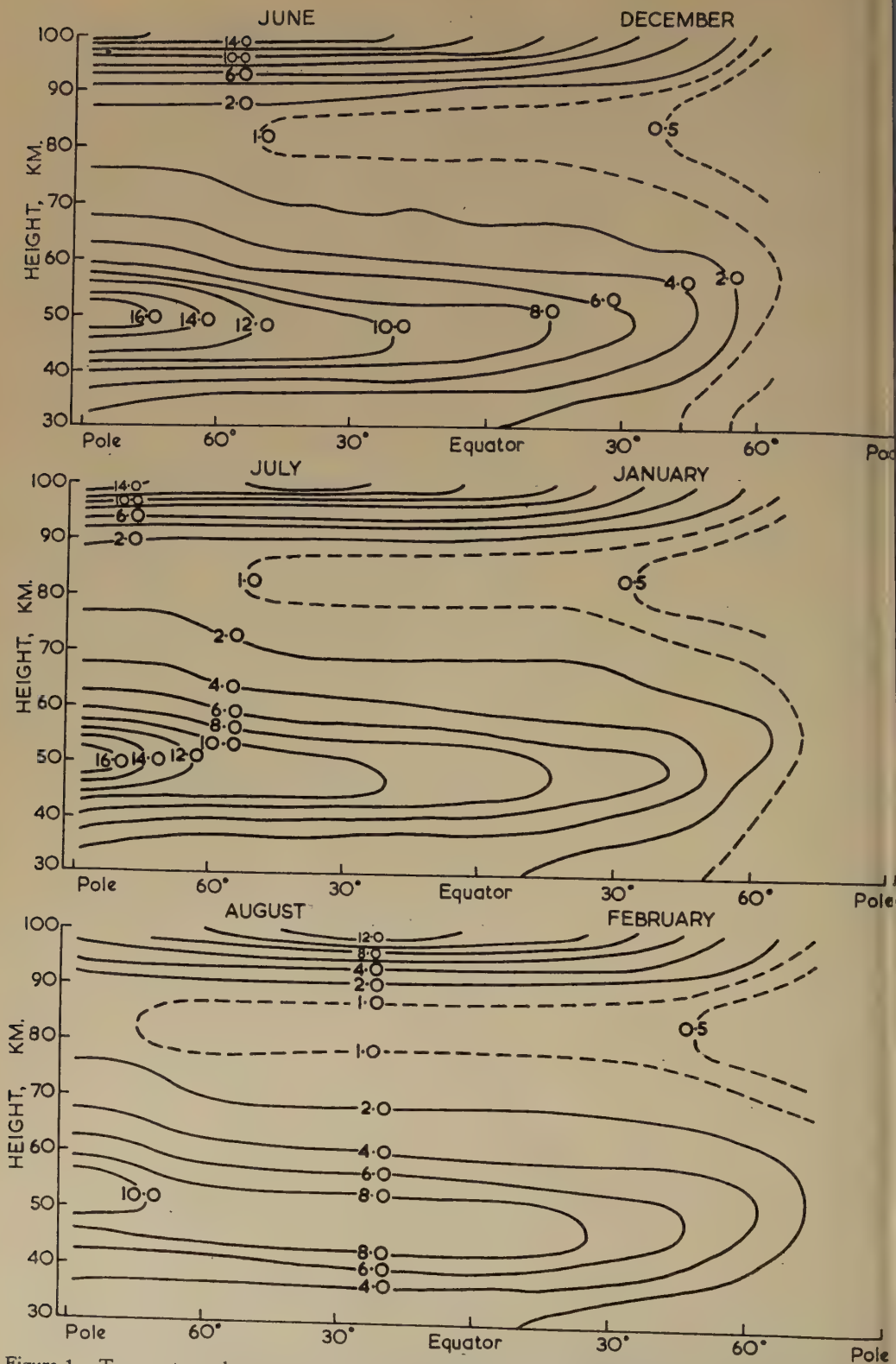


Figure 1. Temperature change caused by solar radiation in °K day^{-1}, assuming that the specific heat per molecule is 7/2 times Boltzmann's constant.

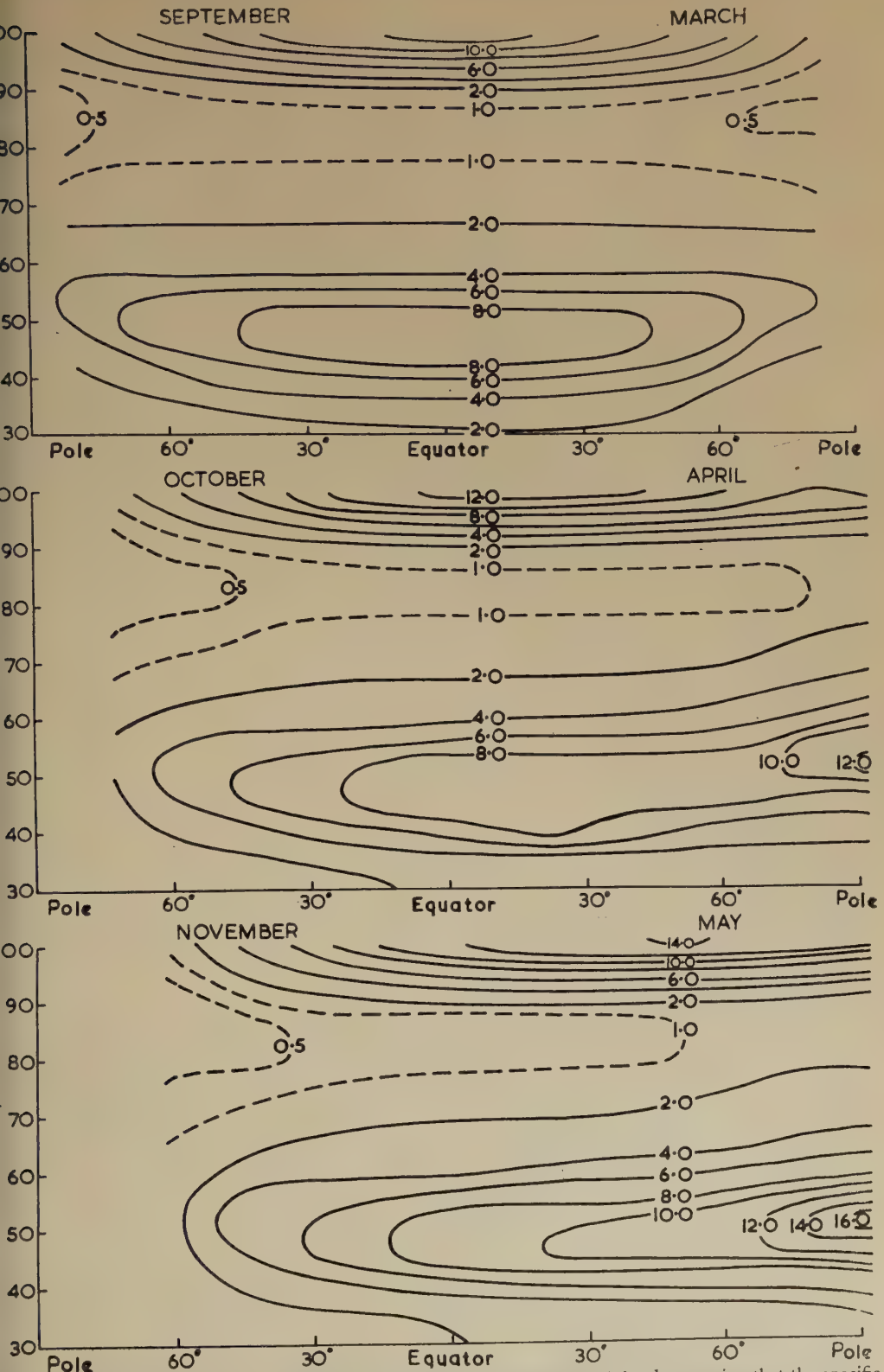


Figure 1 (continued). Temperature change caused by solar radiation in °K day^{-1}, assuming that the specific heat per molecule is 7/2 times Boltzmann's constant.

The general properties of the heating rate as a function of height, latitude and seas have been discussed before, particularly by Pressmann (1954), so that discussion ne not be repeated here. Our results differ from Pressmann's in the main because we ha taken molecular oxygen into account, and because the ozone distribution adopted him has more ozone below 40 km but less above than that used in this paper. As a con quence of the differing ozone distributions, our heating rates are less than Pressman below 40 km and greater above. A comparison is shown in Table 2.

There are many possible sources of error in our work, not all of which are importa Back-scattered radiation from the troposphere has been neglected on the ground that t double passage through the ozone layer will rob the return stream of all energy in spect regions where the atmosphere above 30 km can absorb.

Uncertainties in the intensity of the solar spectrum and gaseous concentrations affe mainly the molecular oxygen absorption. There is also still some disagreement about t influence of pressure on the oxygen absorption coefficients, so the top section of Fig may be in considerable error.

The results for ozone are much more precise. The total heating for all levels combin should be reliable, but variations in the vertical distribution are possible. One improv ment in the data has been established since we undertook these computations. Hear Walshaw and Wormell (1957) have shown that the ultra-violet coefficients of Vigro (1953) are much more accurate than those of Ny and Choong (1933) upon which Cra based his data; Vigroux's coefficients are about 15 per cent lower. The effect of th error is complex, for theoretically and observationally derived ozone concentrations a usually based on these incorrect coefficients; there should therefore be much cancellati of errors in this computation. Since a complete revision of data and computati is not possible, we have been unable to form a numerical estimate of errors, but w believe them to be small.

4. The 15 μ carbon-dioxide band

This is the only strong band of carbon dioxide in the range of wavelengths importa for terrestrial radiation and we were fortunate enough to obtain details of a computi scheme for this band briefly described by Curtis (1956). The scheme is only a preliminar attempt and has a number of sources of inaccuracy; nevertheless we believe that th uncertainties are not sufficient to rob the results of all meaning and it is the only on available into which an arbitrary temperature distribution can be put without recours to an electronic computer. We used Curtis's numerical coefficients without an modifications.

Curtis's computing scheme applies to an array of non-overlapping absorption line whose intensities follow the distribution (1) and to a gas whose mixing ratio does not var with height. At low levels a Lorentz line shape is assumed with line width proportiona to the pressure. At high levels lines will have the Doppler shape and the transition fro one regime to the other is based on the assumption that the matrix elements in Eq. (2 below are a linear combination of the matrix elements which would be obtained usin Doppler or Lorentz shapes alone. The interaction between levels with different pressure and therefore different line widths is taken into account by means of a simple approxima tion which is remarkably accurate even under the worst circumstances (Curtis 1952 Godson 1953). The angular integration is performed analytically. The computatio yields flux divergence directly, the usual difficulties with excessive cancellation bein eliminated by assuming that the Planck functions at five successive datum levels can b fitted by a fourth degree polynomial.

For the computation the atmosphere is divided into equal steps of 0·2 i $\log_{10}$ (pressure), i.e. approximately 3 km steps. The heating rate at the level j is the given as a linear sum over all other levels i.

$$\left(\frac{d\theta}{dt}\right)_j = K\frac{n\alpha_0}{p_0}\gamma \sum_i \pi B_i F_{ij}(\gamma) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where

B_i = Planck function at the centre of the 15 μ band at the level i (erg cm^{-2} sec^{-1} ster^{-1} wave number^{-1}),

$\gamma = \dfrac{\sigma\mu p_0}{2\pi g\alpha_0}$,

σ = mean line intensity from (1) (wave number gm^{-1} cm^2),

μ = mass mixing ratio,

α_0 = line width at pressure p_0 (wave number),

g = acceleration due to gravity (cm sec^{-2}),

n = total number of lines in the array,

θ = temperature (°K)

t = time (days)

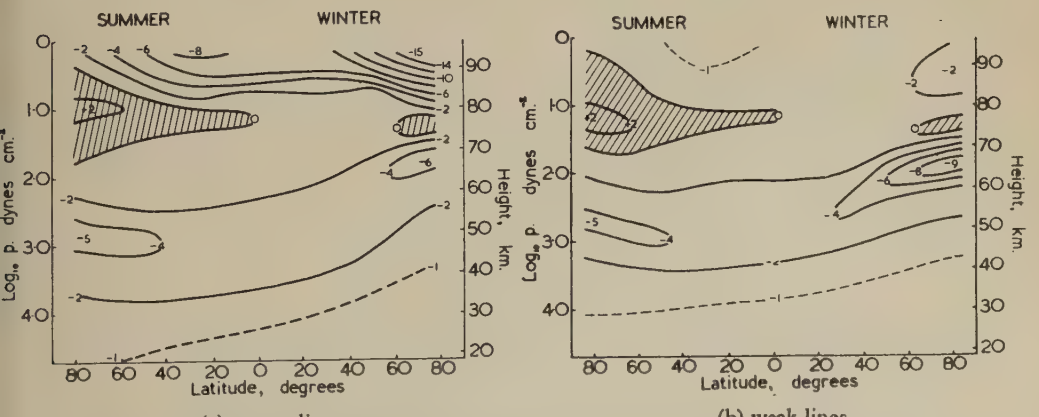
$K = \dfrac{4\pi g s}{c_p} = 106$ deg cm^{-1},

c_p = specific heat (erg gm^{-1} deg^{-1}),

$s = 24 \times 3{,}600 =$ sec day^{-1}.

The non-dimensional elements of the matrix F_{ij} were computed by Curtis for $\gamma = 5$, 100, 560, 620 and 950. For the strong lines $\gamma_s = 935$ and we made use of the elements for $\gamma = 950$, with a slight compensating adjustment to the number of lines in the array. For the weak lines $\gamma_w = 33$ and a new matrix had to be interpolated. In the Lorentz region the elements are proportional to $\gamma^{\frac{1}{2}}$, while in the Doppler region they are proportional to γ; between these two regions a graphical interpolation was made.

Strong and weak line cooling rates from 20 to 95 km are shown in the Figs. 2 (a) and (b). The levels below 30 km are computed because the summation in (2) had to be taken down to the ground and therefore climatological means for the lower levels had to be added to Murgatroyd's data. The effect of the new data is small, however, and details need not be given.



(a) strong lines (b) weak lines

Figure 2. Temperature change caused by the 15 μ carbon dioxide band (°K day^{-1}).

As regards the accuracy of these computations, it is our opinion that Curtis's scheme represents a marked advance in principle over previous methods, quite apart from its flexibility and ease of use. The assumption of non-overlapping lines restricts its usefulness, however, not seriously for P- and R-branches; but the cooling from Q-branches below 50 km will be overestimated.

The scheme also makes no allowance for the effect of temperature upon line intensities. Curtis (unpublished) has shown that errors are very small for that part of the band (the ν_2 fundamental) which provides most of the strong lines, but it will not be negligible for the flanking combination bands which provide most of the weak lines.

Our computations agree tolerably well with those of Plass (1956) for one of the temperature distributions used by him over the height range (25 to 60 km) for which the results are comparable, even though one of us (see Plass 1957) has criticised the methods used even more strongly than those used in this paper (Table 3). It may perhaps be that criticism of both methods has been too severe and that our results are reasonably precise even down to 30 km.

TABLE 3. 15 μ BAND TEMPERATURE CHANGES (°K day^{-1}) FOR THE TEMPERATURE DISTRIBUTION GIVEN BY THE ROCKET PANEL (1952), AS CALCULATED BY PLASS (1956) FOR $\mu = 5 \times 10^{-4}$ AND BY US FOR $\mu = 3{\cdot}65 \times 10^{-}$

Height km	25	30	35	40	45	50	55	60
Plass	− 1·3	− 2·3	− 3·3	− 4·5	− 4·9	− 4·6	− 4·0	− 2·2
This paper	− 1·7	− 2·8	− 4·1	− 5·2	− 6·6	− 6·8	− 5·0	− 3·6

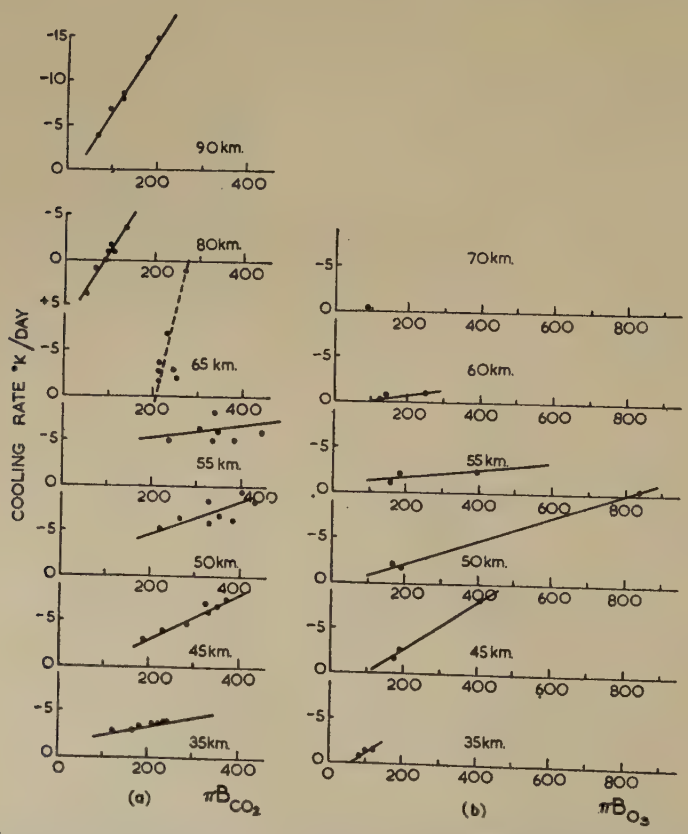


Figure 3. (a) Temperature changes for the 15 μ carbon dioxide band as a function of the Planck function at the band centre. (b) The same for Plass's results (1956) on the 9·6 μ ozone band.

Above 75 km the computed cooling by carbon dioxide becomes unreasonably large f Kirchoff's law is used (Curtis and Goody 1956) and allowance must be made for ibrational relaxation. A simple first approximation was shown by Curtis and Goody to e reasonably accurate, and, using their numerical value for the relaxation time of carbon lioxide, corrections have been made using their Eq. (13). The required cooling-to-space erms are derived from an extra row provided in Curtis's matrices.

5. The 9·6 μ ozone band

This is the dominant band of ozone in the planetary spectrum, and others have been eglected, but a more precise treatment at a later stage should include the effect of the 4·1 μ band.

Provided we consider only temperature distributions of approximately the same shape ve may show from Eq. (2) that as a very rough approximation

$$\left(\frac{d\theta}{dt}\right)_j = k_1 B_j + k_2, \qquad (3)$$

where k_1 and k_2 are constants involving gradients of the Planck function (assumed constant).

In Fig. 3 (a) some computed cooling rates for the 15 μ carbon dioxide band have been plotted against the Planck function at the same level, and the applicability of Eq. (3) is demonstrated empirically. We believe therefore that we are justified in plotting Plass's results against the Planck function at the centre of the 9·6 μ band (Fig. 3 (b)) and making a linear interpolation for the conditions required in this paper. This leads to the results shown in Figure 4, the data for which are taken without modification from Plass's paper.

6. Discussion of the results

Fig. 5 shows the effect of combining the results of §§ 4 and 5 with the results of § 3 for the two solstices (because Murgatroyd's mean temperatures are for near the solstices only). The most interesting result is the degree of cancellation between sources and sinks.

From 30° in the winter hemisphere to 60° in the summer hemisphere (that is over most of the earth's surface) the heating rates below 85 km rarely lie outside the limits $\pm$ 2°K day^{-1}. There is, of course, no *a priori* reason for such a close radiative balance at all levels, but it is an unlikely result to arise by accident. Our interpretation of this result is therefore that our calculations are of a useful accuracy and that there may be comparatively little vertical transfer of heat by non-radiative processes in this region of the atmosphere.

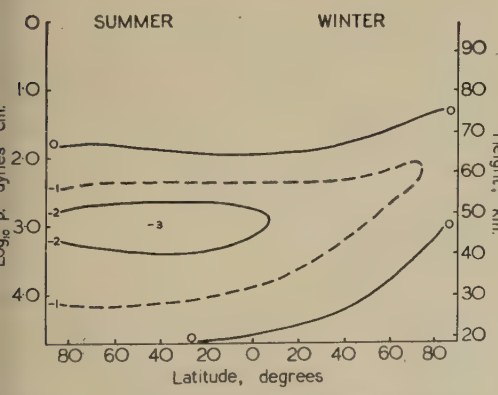


Figure 4. Temperature changes caused by the 9·6 μ ozone band °K day^{-1}.

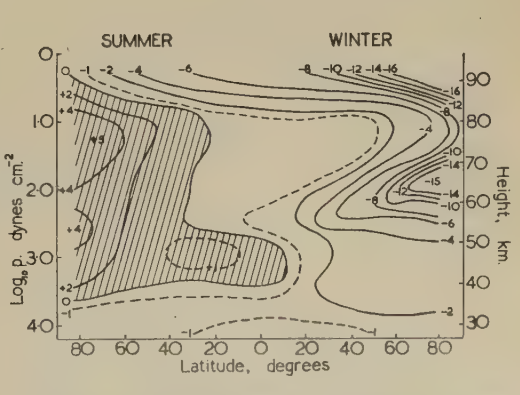


Figure 5. Radiative sources and sinks of heat between 30 and 90 km for the summer and winter solstices °K day^{-1}.

The reasoning behind Eq. (3) and Fig. 3 allows us to estimate the adjustment to temperature required to compensate such a heating rate, and depending upon the altitude we find it to lie between 0 and $\pm$ 15°K. This corresponds approximately to the uncertainty of the temperature measurements themselves so that errors from this cause alone could account for the deviation from radiative equilibrium; within the accuracy of the data and computing methods therefore this part of the atmosphere is in radiative equilibrium.

At the poles, on the other hand, there appear to be significant deviations from radiative equilibrium, with heating from 40 to 90 km at the summer pole and cooling above 30 km at the winter pole. Thus motions at these levels probably transfer heat directly from summer to winter pole. It is not the purpose of this paper to discuss the dynamical consequences of such a distribution of sources and sinks of energy, and it will suffice to remark that it requires a dynamical state fundamentally different from that of the troposphere.

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Ice-nucleating properties of some natural mineral dusts

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Summary

A fairly wide range of 28 naturally-occurring mineral dusts has been tested for ability to act as e nuclei. 19 substances, mainly silicate minerals of the clay and mica groups, are found to be effective at - 18°C; seven of these are active above — 10°C. The most abundant of these is kaolinite with a threshold mperature of — 9°C. 10 of the 28 substances, again mainly silicates, are found to become more efficient e nuclei having once been involved in ice-crystal formation, i.e. they can be pre-activated. Thus, ice crystals rown on kaolinite nuclei, which are initially active at — 9°C, when evaporated and warmed to near 0°C a dry atmosphere, leave behind nuclei which are thereafter effective at — 4°C. Particles of montmorillo-ite, another important constituent of some clays and initially inactive even at — 25°C, may be pre-ctivated to serve as ice nuclei at temperatures as high as — 10°C.

It is suggested that although such particles can initially form ice crystals only at cirrus levels, when the e crystals evaporate they may leave behind some ' trained ' nuclei which may later seed lower clouds at mperatures only a few degrees below 0°C. On this hypothesis, the fact that efficient nuclei are occasionally ore abundant at higher levels would not necessarily imply that they originate from outer space; indeed, in iew of the poor nucleating properties of some meteoritic material that was tested, it appears that atmospheric e nuclei are predominantly of terrestrial origin, with the clay minerals, particularly kaolinite, a major ource.

1. Introduction

Although a good deal of effort has been devoted to measuring the concentrations of tmospheric ice nuclei which become effective at different temperatures, there is little nformation concerning the nature, origin and properties of the responsible particles. Because the ice nuclei are often less than 1 μ in diameter, and because the concentrations f the more efficient ones are very low (perhaps only 10 m^{-3} at temperatures above — 10°C) nd vary greatly in space and time, they are elusive and difficult to identify.

From an examination of observations made by various workers with expansion- nd mixing-cloud chambers, Mason (1950, 1955) tentatively concluded that the nuclei esponsible for the appearance of ice crystals at temperatures above about — 30°C were olid, insoluble particles probably originating from the ground as particles of soil and nineral dusts, and suggested that the clay-silicate minerals might be particularly effective. On the other hand, Bowen (1953) has suggested that highly efficient nuclei may enter the op of the atmosphere as meteoric dust. Although the evidence hitherto *directly* in favour f soil particles being the main source of ice nuclei, which is summarized in § 2, is dmittedly scanty, the evidence in favour of the meteor-dust hypothesis is entirely nferential. In this paper we describe experiments in which a number of mineral dusts ave proved effective as ice nuclei at temperatures above — 18°C while two of the three inely-dispersed specimens of stony-meteorite material failed to produce ice crystals at emperatures as low as — 25°C.

2. Summary of previous work

Schulz (1948) prepared samples of water which could be supercooled to — 20°C in lass capillary tubes and introduced known quantities of foreign particles to study their fficiency as freezing nuclei. The most effective of the agents tested were freshly-ground ea sand (— 3°C), ordinary sand (— 5°C), stony meteorite (— 9°C), tridymite (— 10·5°C) nd graphite (— 9°C), the figures in brackets indicating the threshold temperatures for the

onset of freezing. Most of these substances are silicates. However, because of the potenti nucleating effects of the glass walls and the fact that the variability of the results for particular substance was often greater than the difference between the threshold temper tures for different substances, the significance of these results is doubtful.

Schaefer (1950) sprayed suspensions of various dusts into a mixing-cloud chambe a number of soils collected from different parts of the United States produced some id crystals at temperatures between — 12°C and — 20°C, but the bulk of the particles we not effective until the temperature of the cloud fell below — 25°C. In reporting on th results of a long series of ice-nucleus counts made on Mt. Washington with a cold chamb cooled to — 20°C, Schaefer (1952) cites evidence for the very high counts being associate with the arrival of air which had passed over the arid regions of the United States durir periods of dust-storm activity.

Pruppacher and Sänger (1955) found quartz, porcelain, clays, olivine (an orthosilicat and activated charcoal to be effective below — 12°C in a supercooled cloud, while Ham and Itoo (1956) found that kaolinite, amphibole, augite, all silicate minerals, induced th freezing of supercooled water droplets suspended in silicone oil at temperatures belo — 10°C.

More direct, though rather fragmentary evidence in favour of silicaceous particle comes from the detection of comparatively large insoluble particles at the centres of sno crystals by Kumai (1951) and Isono (1955). With the aid of the electron microscop Kumai examined the nuclei of 43 crystals and found 35 of them to contain soil particle Isono used electron diffraction to identify 15 of 20 snow-crystal nuclei as clay particle probably kaolinite or montmorillonite, of diameter $< 5\ \mu$.

Observations that the ice nuclei activated in expansion chambers at temperatur above — 32°C were much less abundant over the sea and in the upper air (Cwilong 1948 and also above inversions, stratus cloud layers and the haze top (Palmer 1949), point t the ground as being the main source. On the other hand, Smith and Heffernan (1954 and Murgatroyd and Garrod (1957) find that, on occasions, the ice-nucleus concentratio are rather higher above inversions than below.

3. The initial ice-nucleating ability of natural mineral dusts

The present tests were carried out in a sealed glass vessel immersed in a thermostati ally controlled refrigerator, this system being preferred to the usual open-top cold bo because it could be kept scrupulously clean and free from contamination by atmospheri aerosols. A 5-litre ' Pyrex ' flask, after being carefully cleaned, is placed in the refrigerato flushed with clean filtered air until cooled to the required temperature and then sealed After the air inside the flask has reached a steady temperature as indicated by suitabl disposed thermocouples, the material under test is introduced as a fine dust through a sid tube, and a supercooled cloud is formed by evaporation from a piece of water-soake gauze, heated by a small electric bulb. The temperature variations within the flask ar less than 1°C even with the water source in operation. The appearance of ice crystals ca be detected by their glittering in a beam of light traversing the chamber, but it prove much more convenient to use the supercooled-film technique described by Mason an Hallett (1957).

A film stretched across a wire hoop, about 2 in. in diameter, and made by dippin the latter into a mixture of the liquid detergent ' Stergene ' and water, is suspended insid the flask.

When tiny ice crystals fall on the supercooled film they grow quite rapidly and produc much larger crystals which are easily seen and counted (see Plate III, Fig. 1). A number c preliminary tests were made on these films to determine the constitution of the mixtur which would give optimum stability and sensitivity. This was roughly a 50/50 solution c ' Stergene ' and water, giving films which were quite stable for periods of several hours, an on which ice crystals grew at rates of 0·1 to 10 mm/sec, depending on the temperature

Figure 1. The nucleation of a supercooled film by tiny ice crystals.

The films can be used successfully down to temperatures of − 15° to − 18°C, but at lower temperatures they soon become nucleated by the metal supporting ring. An estimate of the concentration of ice crystals in the cloud may be made from the rate of appearance of crystals on the film; one crystal appearing every 30 sec corresponds to a concentration of about 1/li under the particular conditions of this experiment. As about 30 is the maximum number of crystals which can appear on the film within 10 sec without it freezing all over, the maximum concentration which can be detected is about 100/li.

The minerals to be tested are ground with a pestle and mortar, care being taken to prevent one substance from becoming contaminated with small traces of another. Several samples of each material are ground and tested separately in order to reduce and detect the possibility of such contamination. The powders so produced contain an appreciable fraction of micron and sub-micron particles. They are stored in polythene bottles fitted with outlet tubes through which they are dispersed into the test flask by squeezing the bottle after shaking.

Each substance was tested for ice-nucleating ability down to − 18°C; any substance not producing crystals on the film at − 18°C was tentatively listed as inactive. Active substances were tested at successively higher temperatures to determine a threshold temperature for their activity. This limit was inevitably somewhat arbitrary, but was taken as the highest temperature at which up to 4 crystals appeared on the film within two minutes, corresponding to a crystal concentration of about 1/li in the cloud, and roughly one dust particle in ten thousand acting as an ice nucleus. For each active material, at least 6 tests were made on separately ground samples. At temperatures above − 15°C, when spurious nucleation, for example by frost splinters from the walls, could be almost entirely eliminated the threshold temperatures for individual tests on the same material never varied by more than 0·5°C from the mean value.

The results of tests on 28 different substances are listed in Table 1. These include 17 different silicate minerals, mostly clays, micas and varieties of quartz. Some miscellaneous minerals, e.g., vaterite ($CaCO_3$), covellite (CuS) and hematite were chosen because

TABLE 1. SUBSTANCES INITIALLY ACTIVE AS ICE NUCLEI AT TEMPERATURES ABOVE − 18°C

Substance	Crystal structure	Lattice parameters	Threshold temp. (°C)
Covellite (CuS)	Hex.	$a = 3{\cdot}80$, $c = 16{\cdot}43$ A	− 5
Vaterite ($CaCO_3$)	Hex.	$a = 4{\cdot}12$, $c = 8{\cdot}56$	− 7
*β – Tridymite†	Hex.	$a = 5{\cdot}03$, $c = 8{\cdot}22$	− 7
*Kaolinite	Triclinic	$a = 5{\cdot}16$, $b = 8{\cdot}94$, $c = 7{\cdot}38$	− 9
*Microcline			− 9·5
Glacial debris			− 9·5
Hematite (Specularite)	Hex.	$a = 5{\cdot}03$, $c = 13{\cdot}75$	− 10
Aquadag (colloidal graphite)			− 12
*Volcanic ash			− 13
*Halloysite†	Monoclinic	$a = 5{\cdot}16$, $b = 8{\cdot}94$, $c = 10{\cdot}1$	− 13
Dolomite†	Hex. (rhomb)	$a = 6{\cdot}02$, $\alpha = 47{\cdot}5°$	− 14
*Biotite			− 14
*Vermiculite	Monoclinic	$a = 5{\cdot}34$, $b = 9{\cdot}20$, $c = 28{\cdot}91$	− 15
*Phlogopite			− 15
Cinnabar†	Hex.	$a = 4{\cdot}14$, $c = 9{\cdot}49$	− 16
Gypsum	Monoclinic	$a = 14{\cdot}5$, $b = 15{\cdot}2$, $c = 6{\cdot}5$	− 16
Graphite (pencil lead)	Hex.	$a = 2{\cdot}46$, $c = 6{\cdot}70$	− 16
*Anorthoclase			− 17
Stony meteorite (one sample)			− 17

Substances inactive above − 18°C include:
Montmorillonite, sepiolite, albite†, muscovite†, orthoclase, talc†, sand, quartz, α – tridymite, two samples of stony meteorites.

* silicates. † Not of a high degree of purity.

Note added in proof: We have recently found magnetite to act at − 8°C and gibbsite at − 11°C.

of their crystal structures being similar to ice. In addition such materials as volcanic ash and some species of carbon were tested as likely constituents of atmospheric aerosols. Altogether 19 substances were found to provide ice nuclei at − 18°C or higher temperatures, the threshold temperatures of seven of these being above − 10°C. Nine of the active materials were silicate minerals belonging mainly to the clay and mica groups. On the other hand, a number of silicates were inactive at temperatures above − 18°C and some, such as montmorillonite, sand and quartz were not measurably effective even at − 25°C. These results are discussed in greater detail in § 6.

4. The pre-activation of nuclei

The possibility that some ice nuclei may become more effective having once been involved in ice-crystal formation was first suggested by an observation of Fournier d'Albe (1949). He found that although during a first expansion of a cloud chamber CdI_2 nuclei produced ice crystals only below − 41°C and when the air was saturated relative to liquid water, when the ice particles were allowed to evaporate, and provided they were not warmed above − 9·1°C, they left behind nuclei on which ice would grow again after very much smaller expansions, cooling the air only very slightly below the frost point. Mason (1950) suggested, in explanation, that warming to temperatures below − 9·1°C caused only partial evaporation of the ice, a sub-microscopic film being left on the surface of the nuclei, so that in a subsequent expansion the nucleus was, in effect, an ice particle.

This behaviour of CdI_2 nuclei has been confirmed by Mossop (1956), who also found that a small proportion of the particles produced by spraying suspensions of Iceland Spar ($CaCO_3$), gypsum ($CaSO_4 . 2H_2O$) and sodium-bentonite clay behave in a very similar manner.

The retention of an ice film, perhaps only a few molecules thick, or of small ice embryos in suitable cavities on the surface of a nucleus such as have been proposed to explain 'memory phenomena' in the melting and re-crystallization of metals, may enable ice crystal formation to proceed as soon as the particles again enter ice-supersaturated air. Mason (1956) suggested that this may be the explanation of an observation reported by Braham (1955) that residues of snow crystals falling from a cumulus cloud, after being warmed to + 13°C in a chamber for 2-3 min, formed ice crystals again when introduced into a supercooled cloud at temperatures just below 0°C, whereas nuclei sampled in clear air were active only below − 33°C.

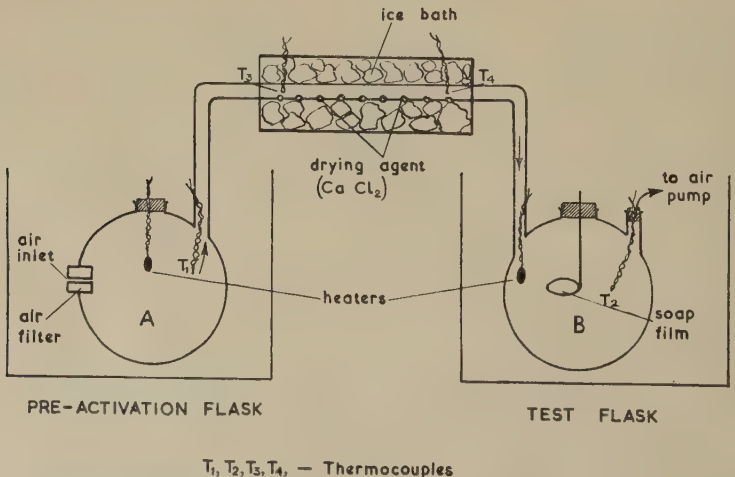

Figure 2. The apparatus used in studying the pre-activation of ice nuclei.

In the present experiments all the materials were tested to see whether they could be pre-activated in the sense just described. The apparatus is shown in Fig. 2. Nuclei, initially activated in chamber A at a temperature recorded by thermocouple T_1, were drawn through a glass tube 50 cm long × 1·5 cm diameter in a stream of filtered air, and into the second chamber B containing a thermocouple T_2 and a 'soap' film detector. The transit tube containing calcium chloride was surrounded by an ice and salt bath; the air temperature in the tube, recorded by thermocouples T_3 and T_4 placed 5 cm from each end, was controlled by the flow rate of the air, and was usually held at a temperature between − 3°C and + 1°C. The temperature of the whole system came to equilibrium within half to one minute of starting the air flow with the temperature in the tube being constant along the last two-thirds of its length. The temperature in the first chamber was not affected by turning on the air provided the flow was not continued for more than 5 min at a time. The transit time of a nucleus between the first and second chamber was about 10-30 sec.

Several preliminary tests were made to ascertain the experimental conditions under which ice crystals, produced by seeding the cloud in chamber A with dry ice, would not be carried over into the second chamber B, but would be completely evaporated during their passage through the connecting tube; these conditions were then satisfied in all subsequent tests of nucleating materials. In any particular experiment, the temperature of the detection chamber was set one degree above the previously determined threshold temperature for the initial activity of the substance, the material was dispersed in chamber A, and the resulting ice crystals drawn through the tube. If several trials with a minimum transit temperature (T_4) of − 5°C and a minimum transit time failed to produce ice crystals in B, then the material was considered not to respond to pre-activation. But if crystals appeared on the supercooled film within 20 sec, the nuclei were provisionally listed as having been pre-activated. In such a case, the procedure was repeated a number of times, with the temperature of the detection chamber raised in steps of one degree, until the threshold temperature for the pre-activated nuclei was determined. Variation of the temperature in the transit tube between − 5°C and 0°C appeared to have little effect, but if the temperature of T_4 rose above + 1°C, the residual nucleating properties of all particles were completely destroyed.

The 10 substances which were successfully pre-activated are listed in Table 2; only 7 of these appear in Table 1 as having threshold temperatures above − 18°C. Table 2 does, however, include montmorillonite (bentonite) which, initially, was inactive above − 25°C, but produced ice crystals below − 10°C after pre-activation; this confirms Mossop's observations. We are unable, however, to confirm his results with gypsum and Iceland spar, although in connexion with the latter substance, we found vaterite, a related form of $CaCO_3$, to respond to pre-activation, and suggest that Mossop's samples of Iceland spar may have contained traces of vaterite.

TABLE 2. SUBSTANCES RESPONDING TO PRE-ACTIVATION

Substance	Threshold temp. for initial activity (°C)	Temp. T_4 in transit tube (°C)	Threshold temp. after pre-activation (°C)	No. of trials
Vaterite	− 7	− 4	− 4	5
*Kaolinite	− 9	− 0·5	− 4	12
Glacial debris	− 9·5	− 1·0	− 5	20
*Volcanic ash	− 13	− 1·5	− 7	20
Cinnabar	− 16	− 2·0	− 7	25
Graphite	− 16	− 0·5	− 9	10
Stony meteorite	− 17	0	− 10	10
*Albite	< − 18	− 3	− 9	8
*Sepiolite	< − 19	− 3	− 14	17
*Montmorillonite	< − 25	− 2	− 10	15

All other substances listed in Table 1 were found not to respond to pre-activation.

* Silicates.

5. The nucleating ability of meteoritic material

The only published account, known to the authors, of meteoritic material being tested for ice nucleating properties is that of Schaefer (1957), who vaporized a piece of iron-nickel meteorite by an electric spark in a supercooled cloud. No trace of ice-crystal formation could be detected, even in clouds as cold as − 25°C, although large numbers of particles were formed. We have tested *stony* meteorites because Bowen suggests that these are likely to be the source of effective nuclei. Our three samples were all of the aerolite variety; careful analysis gave their constitution as 90 per cent silicates, mainly pyroxene, and the remainder chiefly iron oxides. Two of the specimens, found near Holbrook, Arizona, when vaporized by an electric spark or ground up as a fine powder produced no ice crystals in a supercooled cloud at temperatures down to − 25°C and none of the nuclei responded to pre-activation. The third sample, from Huguton, Kansas, produced nuclei initially active below − 17°C, and after pre-activation, a small fraction of these became effective at − 10°C.

6. Discussion of results

Of the 19 substances which nucleated a supercooled cloud at temperatures of − 18°C or above, kaolinite is by far the most abundant; all the other materials, with the exception of volcanic ash, occur as only minor constituents of soils. Clays are composed predominantly of either kaolinite or montmorillonite (bentonite), the latter being initially inactive as a nucleating agent above − 25°C. Kaolinite, which is the dominant clay-mineral component of tropical and sub-tropical soils and is also present to a variable extent in the soils of Europe and the north and eastern parts of the United States, occurs mainly in the form of six-sided plate-like particles of diameter 0·3 μ to 10 μ; these induce ice crystal formation initially at temperatures below − 9°C and, after pre-activation, at − 4°C. To check on the possibility that particle size might alter the effectiveness, two-sized samples of kaolinite were obtained and tested – one composed of 0·2 to 0·5 μ diameter particles, the other of 5-10 μ diameter particles. No difference in the threshold temperatures could be detected, indicating that, if there is a size dependence, it is a relatively small effect. Apart from covellite (CuS), vaterite and β-tridymite which occur naturally in only negligible quantities, kaolinite is the most effective of the 28 substances tested, and it therefore appears that this may well be the main source of efficient atmospheric ice nuclei. But, because most of the clay soils are covered with vegetation, the quantities of kaolinite particles carried up into the atmosphere are probably small compared with those of desert soils; however, the latter are composed mainly of sand (quartz) with smaller amounts of montmorillonite and micas, all of which are relatively inactive as ice nuclei.

Microcline, halloysite, vermiculite, and the biotite and phlogopite micas, all of which are minor silicaceous constituents of some clays, are probably significant subsidiary sources of nuclei.

Since clays and other silicate minerals are produced by the weathering of igneous rocks, it is likely that volcanic ash will contain a mixture of these substances and therefore that its ice-nucleating ability will be similar to that of the more efficient clays. Our value of − 13°C for the threshold temperature of a sample of ash from Mt. Etna is the same as that reported by Isono (1955) for material from Mt. Asama (Japan) and close to Schaefer's (1952) value of − 16°C for dust from Mauna Kea and Mauna Loa in Hawaii.

The high nucleating efficiencies of covellite, vaterite and β-tridymite may be related to the fact that they are all hexagonal crystals with well-defined basal planes in which the *a* lattice spacing is within about 10 per cent of the corresponding one in ice. But, in view of the lack of detailed information available on the crystalline structure and surface properties of the silicate minerals, it is not possible to explain convincingly the differences in the nucleating abilities of the other minerals listed in Table 1. The reason that kaolinite is highly effective while montmorillonite, a structurally similar constitutent of clays, is initially inactive, is probably that kaolinite consists of alternate layers of gibbsite ($Al_2(OH)_6$) and silica, with gibbsite, which is active as an ice nucleus at − 11°C, always

posed, while montmorillonite, with gibbsite layers sandwiched between two silica ers (S G S S G S), cleaves to produce surfaces of silica, which is certainly inactive r ice nucleation at temperatures above − 25°C. The fact that montmorillonite particles ve been shown to contain cracks intersecting at 120° may be important in the formation of able ice embryos. While some of the other materials that successfully respond to pre-tivation, such as the fibrous clay mineral sepiolite, may retain ice embryos within the ystal structures, others may simply hold ice-like aggregates of molecules on surface disloca-on sites. However, the fact that the pre-activation of the nuclei is destroyed once they are ated above 0°C suggests a melting of embryos rather than a complete evaporation of rface layers. It is perhaps significant that the very hard, non-porous minerals such as uartz, tridymite, microcline and orthoclase, and also the sheet-like micas, all of which obably contain very few surface cavities and do not adsorb water strongly, do not spond to pre-activation.

The fact that particles of a number of minerals such as montmorillonite can be pre-tivated or ' trained ' as ice nuclei may be of considerable meteorological significance. lthough in our experiments the nuclei were subjected to the de-activation treatment for eriods of only ½ min, the conditions of both temperature and humidity were much more vere than would normally be experienced at sub-freezing temperatures in the atmosphere. he results therefore suggest that although such particles may initially form ice crystals nly at the low temperatures normally associated with cirrus clouds, when the crystals vaporate they may leave behind some pre-activated nuclei which may later fall down and ed supercooled clouds at temperatures only a few degrees below 0°C. This, together ith the multiplication of ice crystals by the splintering of frozen drops and the fragmen-tion of snow crystals, may account for the rapid glaciation of clouds which is sometimes bserved at these temperatures. If, also, the cirrus clouds may be regarded as a reservoir f efficient ice nuclei, then it appears unnecessary to postulate the arrival of particles from uter space in order to account for the fact that the concentration of such nuclei sometimes ncreases with height above the ground. Moreover, since laboratory tests indicate that the ucleating ability of meteorites is much inferior to that of several substances of terrestrial rigin, the overall evidence appears strongly in favour of the ground being the main source f atmospheric ice nuclei.

Acknowledgment

One of us (J.M.) wishes to acknowledge the receipt of financial assistance from the Defence Research Board of Canada.

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The movement of precipitation belts as observed by radar

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(Manuscript received 30 October 1957, in revised form 17 February 1958)

SUMMARY

The movement of 51 belts of precipitation of cold-front type over south-east England has been measur from radar records and compared with upper winds at each 50-mb level from 950 to 500 mb. The mean spe of the belts is found to be in close agreement with the mean wind component across the belts at the 700-r level, with a correlation in excess of 0·9. Even at 650 and 750 mb the correlation is significantly low while at 950 mb it is only 0·6. The same pattern of correlations and of wind components was found in 31 be associated with occlusion situations, and no significant variation in correlation level was found despite su division of the material on the basis of the height ranges of the observed echoes.

A simple forecasting rule is suggested, that ' belts of precipitation of cold-front type move with a spe equal to the component of the 700-mb wind across them.'

1. INTRODUCTION

Ligda (1953) in a comparison of the radar movements of small precipitation are with winds scaled from upper-air charts found that a much closer correlation existe at 700 mb than at either of the other two levels available to him, 850 and 500 mb, and has been widely accepted that displacement with the 700-mb wind is a good forecastin technique for the movement of isolated showers. The present paper attempts a mo detailed examination of this correlation, not for isolated showers, but for belts of prec pitation, by comparison with measured winds from the British radar-wind network, whic are available at regular 6-hr intervals and at each 50-mb level.

Belts of precipitation are frequently observed on radar having clearly defined edg of echo. Their direction and speed of movement can be rapidly and accurately determine from the plan-position display over a limited area. A clear distinction must be drawn her between the direction and speed of movement of the belt (which is measured normal t its length), and the movement of the individual echoes of which it is composed, for thes will normally have a component of motion along the belt, often a very substantial on which may or not be obvious from radar. On some occasions there may be a continuou process of development and dissipation in addition, with precipitation forming at one sid of a belt, moving through and dissipating at the other. This is sometimes noticeable i the changing radar pattern of isolated cumulonimbus masses, but close study is needed t detect it, and it is probably not an important factor in moving precipitation belts whic have persistent well-defined edges.

Radar is able to define these belt movements accurately from observations coverin as little as half an hour, though admittedly in a relatively small sector. Their movement is in comparison, very hard to define from synoptic charts, even with a close network o weather-reporting stations as in this country.

2. MATERIAL EMPLOYED

(*a*) *Radar material*

Photographic records taken at the Meteorological Office Radar Research Station a East Hill on a 500 kW 10 cm plan-position radar in the five-year period 1947-52 were found to include 51 belts of precipitation where the belt movements could be clearly

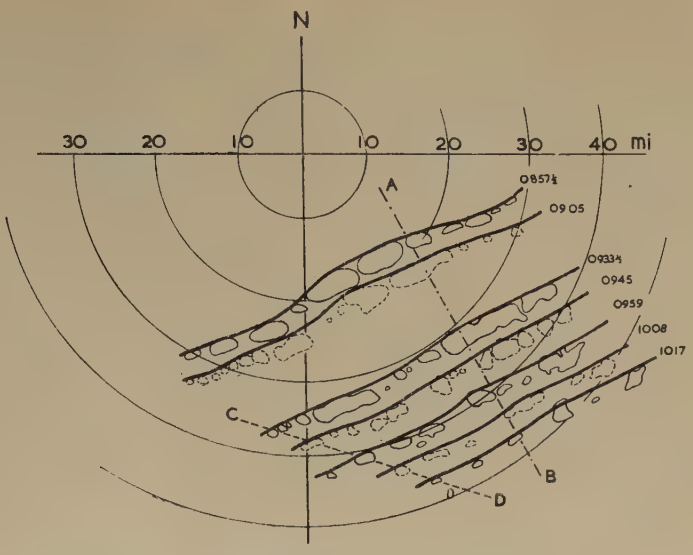

Figure 1. Isochrones of the radar pattern of a belt of precipitation of cold-front type, 4 July 1951 (times in GMT).

defined and associated with cold-front situations in the *Daily Weather Report*. No attempt was made at the time to relate the belts closely to the fronts on the synoptic chart; for example, some were included on the assumption that they could have been secondary cold fronts not essential to the normal scale of synoptic analysis, others were reasonable extrapolations of secondary cold fronts. Usually their orientation was in good agreement with the main cold front shown on the chart and was quite different from that of any more distant front, but exceptions to this were allowed (*e.g.*, belt orientations suggestive of minor frontal waves) since the forecaster inevitably smooths out some smaller-scale features on the synoptic chart, yet these may be a dominant feature of the radar display. This has been taken into account in the analysis by extracting wind components normal to the radar belt. The 51 cases of the main correlation are referred to in this paper as ' belts of cold-front type,' but the rather loose definition should be borne in mind. The average period of measurement of the radar movements of the 51 belts was 66 min, and the average speed of movement 20·7 kt.

Isochrones of a clearly-defined edge of echo were drawn for each belt by projection of the 35 mm plan-position photographs. Slight adjustment of magnification was usually necessary from frame to frame to allow for variations in the voltage of the mains supply. No single adjustment of magnification in the projection process can eliminate a slight non-uniformity in the range scale across the display. This is inherent in any cathode-ray-tube presentation. The residual error can be reduced however by scaling off the echo movements against their own sections of the radial range scale, and is negligible for the present purpose.

An actual plotting is shown at Fig. 1. This is of precipitation associated with a clear-cut but weak cold-front passage, selected because it has enabled the echo pattern at each time to be shown. Observations in this case covered a period of 80 min, and included seven positions of the trailing edge. It can be seen that the belt is nowhere more than 3 mi in width, and would probably not have given more than 10 min of rain in passing. A point that is clearly shown is the difficulty in following individual echo sequences even in as well-defined a belt as this. The general impression of the individual movement is clear (*e.g.*, CD), but for very few of the individual echoes could a direction be given with confidence. There was often a broader belt of continuous precipitation in which such identification was impossible.

The movement of the belts was measured normal to the echo edge (*e.g.*, along A' in Fig. 1), a single value for the speed being determined graphically by plotting th intercepts along AB against time, and taking the slope of the straight line of best fi This gave equal weight to each plotting, and minimised the effect of local irregularitie It might be claimed that the placing of the line AB is rather arbitrary, but the variabilit of measured speed due to this cause is thought to be less than the probable error in th measured winds. Not all the belts were as smooth as this one, and in general some degre of smoothing of slight protuberances and indentations in the echo edge has been necessar

A further 31 belts of precipitation were found in the radar records which we sha refer to as ' occlusion-type belts ' because the associated depression was shown as occlude in the *Daily Weather Report*, but again the definition is a loose one. That they had clea cut edges of precipitation on which measurement was possible suggests that the associate occlusions were probably of cold-front type, and indeed many of the belts were probabl not different in character from some of the 51 belts. The subdivision was convenien however, since they could be correlated separately, and be used as a check on the mai analysis. The average period of measurement for the 31 belts was 80 min, associated wit a rather lower average speed of 15·5 kt.

(*b*) *Upper winds*

The advantages of using measured upper winds for comparison with the belt move ments rather than geostrophic winds scaled from upper-air charts are (1) that they ar available at 6-hr intervals compared with the 12-hr spacing of upper-air charts, so tha there is always a sounding within 3 hr of the time the belt movement is measured, an (2) that they enable correlations at each 50-mb level, whereas upper-air charts are draw at 700 and 500 mb only. The latter was thought to be of special importance.

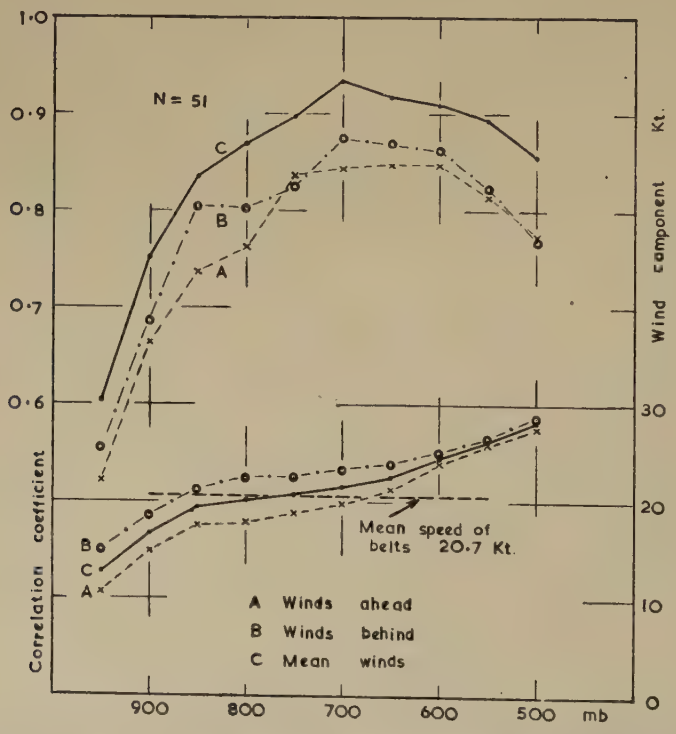

Figure 2. Variation with height of the correlation of movement of 51 belts of precipitation of cold-front type with upper-wind components normal to the belts. The wind components are the lower curves (right-hand scale), and the mean speed of the belts is indicated.

Two radar-wind ascents were used in each case, one of winds ahead, the other of winds behind the belt, the choice of ascents being determined by the orientation of the belt. Whenever possible one was chosen directly downwind and one upwind from the area in which the movement was measured, but it was not possible to hold rigorously to this because of the more limited choice of ascents to the south and east of East Hill. On average the soundings were 40 mi ahead and 100 mi behind the belts, and as close as possible in time (*e.g.*, those used for the belt shown in Fig. 1 were Liverpool and Larkhill at 0800 GMT).

3. Results

(*a*) *51 belts of cold-front type*

The results for the main correlation are shown in Fig. 2. The significant features are :

(1) that the correlations (upper curves) have a well-defined maximum of high significance at 700 mb, and that the best agreement of mean belt speed with the mean wind components (lower curve C) is also close to this level;

(2) that the correlations are much lower at 950 and 500 mb, and that the wind components at these levels differ substantially from the belt speeds;

(3) that the correlations are higher for the mean winds at all levels (upper curve C) than for those ahead of or behind the belts (upper curves A and B), and

(4) that the mean wind components behind the belts (lower curve B) are stronger than those ahead (lower curve A) at all levels.

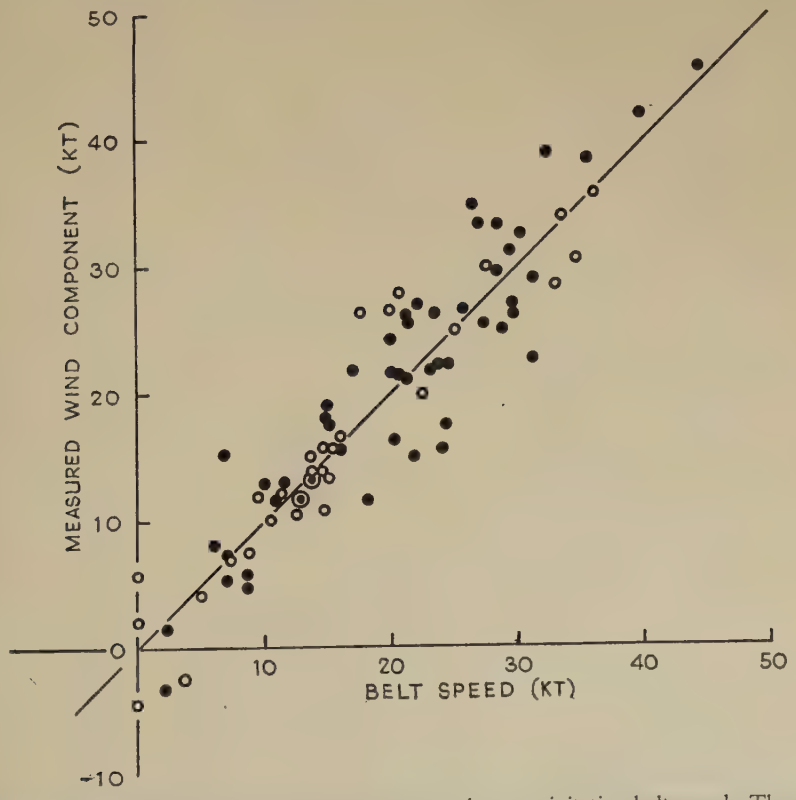

Figure 3. Scatter diagram of 700 mb wind components against precipitation belt speed. The 51 cold-front type belts shown by points, the 31 occlusion-type belts by open circles. The sloping line represents perfect agreement.

It is of interest to compare this with the correlations found by Ligda (1953) for th movement of his small precipitation areas. He compared both the direction and spee of movement of 90 storms with geostrophic winds scaled from upper-air charts at th three levels 850, 700 and 500 mb (Table 1). The variation in speed correlation is in excelle agreement with the form of the curve of Fig. 2.

TABLE 1. LIGDA'S CORRELATIONS FOR SMALL PRECIPITATION AREAS

Pressure (mb)	Correlation with direction	Correlation with speed
850	0·73	0·49
700	0·96	0·81
500	0·87	0·58

Fig. 3 is a scatter diagram of the belt movements at the 700-mb level, with belt spee plotted against mean wind component, for the 51 belts of cold-front type by points, an for the 31 occlusion-type belts by open circles. There is seen to be a broad spread of speed involved, up to a maximum of 45 kt. The sloping line represents perfect agreement An explanation of the negative and zero values is desirable. The direction of movemen of the belt on the radar display was always taken as positive. If the mean wind componen turned out negative this of course adversely affected the correlation at the level concerne (there were two such cases at 700 mb, but the negative components were small). In thre cases shown with zero belt speed, although there was no detectable movement of the bel where the echo edge was well-defined, there was a small movement in some other par of the display. This was then taken as positive, and a wind component opposed to it a negative.

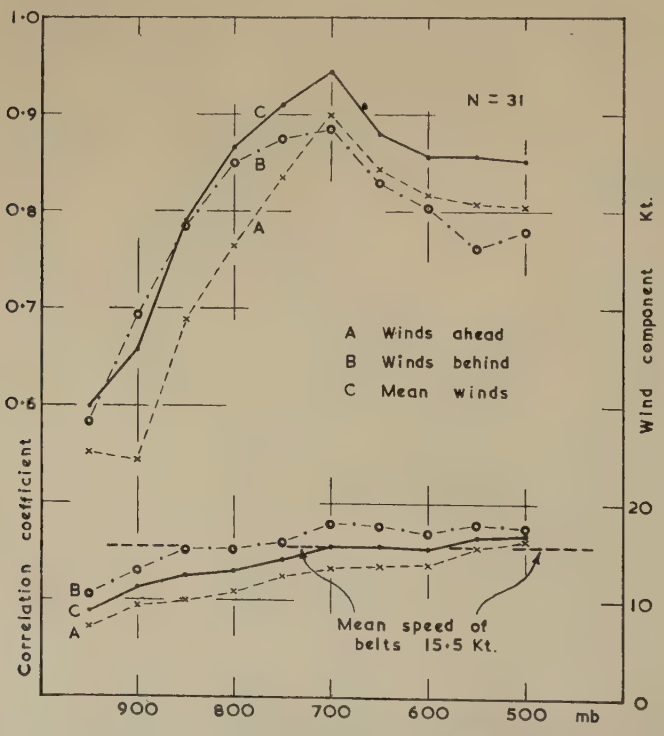

Figure 4. Correlations and wind components for the 31 occlusion-type belts of precipitation (cf. Fig. 2).

(*b*) *31 occlusion-type belts*

To convince ourselves that the main features of Fig. 2 were not fortuitous, correlations
d wind components have been evaluated separately for the 31 occlusion-type belts
ig. 4). The curves are seen to differ in no essential particular from those for the main
rrelation, and would seem to confirm the validity of the maximum of the correlation
rve at 700 mb and of other features to which attention has been drawn in Section 3 (*a*).

(*c*) *Subdivision on basis of height of echo tops*

A further test has been applied by separating the material into ranges on the basis
the heights of the observed radar-echo tops. Range-height information was available
r 77 of the total of 82 belts. In most cases precipitation was continuous from echo-top
vel to the ground, either as diffuse echo, or with some column structure (in a few cases
e echo top was associated with an upper layer-type echo which may or may not have
en related to the rain reaching the ground). No attempt has been made to discriminate
tween these types. The heights of maximum echo top are analysed into various height
nges in Table 2. Note that only seven of these 77 belts have a maximum echo top at
),000 ft (700 mb) or below. There are 42 cases with echo tops above 18,000 ft (500 mb),
nd 35 with echo tops below 18,000 ft. This seemed a convenient division of the material,
nd the wind components for these classes have been correlated and meaned separately
Fig. 5) to see if any variation in level of maximum correlation can be related to the radar
ppearance. It will be seen that the highest correlations for both classes are still at 700 mb,
nd the mean wind components at 700 mb are within 1 kt of the mean belt velocities. This
uggests that there is no substantial variation of height of ' steering level ' with vertical
xtent of precipitation.

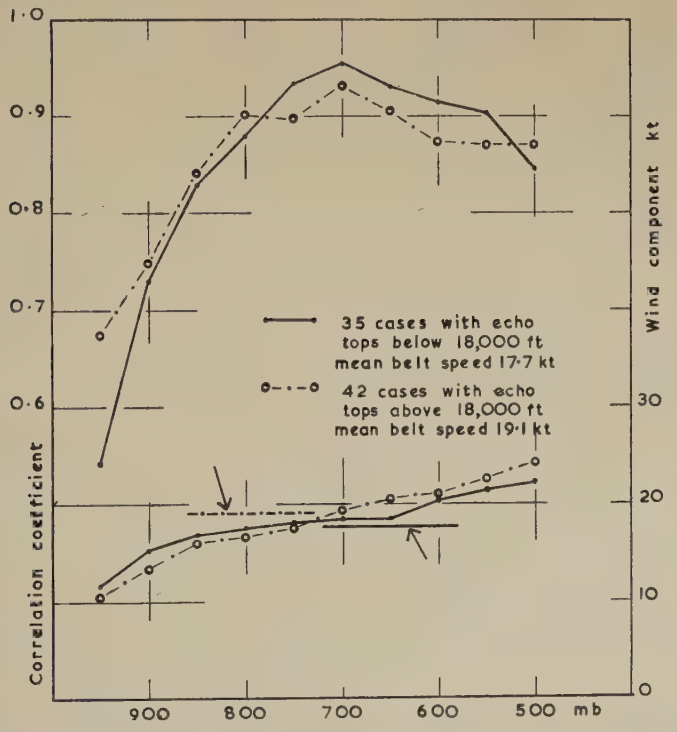

Figure 5. Division of precipitation belts on the basis of height of echo tops. Correlations and mean wind components for 35 cases with echo tops below 18,000 ft, and for 42 cases with tops above 18,000 ft. The mean belt speeds for each category are indicated by arrows. The curves are seen to differ in no essential particular from those of Fig. 2.

TABLE 2. NUMBERS OF OCCASIONS WITH MAXIMUM RADAR ECHO TOPS FALLING IN THE GIVEN HEIGHT RANGES

Height range (10^3 ft)	Cold-front type belts	Occlusion-type belts	Total
0-5	0	0	0
6-10	3	4	7
11-15	15	8	23
16-20	11	9	20
21-25	12	4	16
26-30	3	3	6
31-35	2	2	4
36-40	0	1	1
Total	46	31	77

4. DISCUSSION

It is of interest to consider whether the wind regime represented by the mean curv of Fig. 2 is a possible one if we assume a simple cold-front structure, a surface of dis continuity of uniform slope, moving with the speed of the belts. If this slope were 1 in 5 (a widely accepted though not well authenticated value for cold fronts in the British Isles the cold air would extend up to the 700-mb level at 100 mi where on average the wir measurements were made. We suggest tentatively that a reason for the wind curves and B closing in above 700 mb and becoming almost coincident at 600, 550 and 500 m could be that the measurements were being made in the same air mass above such a front surface.

Behind our assumed front and below 850 mb the wind components (curve B) are les than the belt speed, representing a considerable deficit of air. This can be made up fro the surplus available at levels between 850 and 700 mb in the cold air where the win components exceed the belt speed, and would accord with experience that there is usuall subsiding motion in the cold air behind a cold front.

Ahead of the front, on the other hand, warm air is being overtaken by the front surface at all levels below 700 mb (curve A), and since the low-level wind component are little more than half the 20·7 kt frontal speed, a substantial amount of air is involve To dispose of this otherwise than by lifting would require either a rapid acceleration of a parallel to the front, or an equally rapid deceleration of the frontal surface itself, and i is reasonable to think that not more than a small part of the overtaken air could be deal with in this way. If we neglect these effects we can compute from suitable environmen conditions an average rainfall associated with the passage of the front.

We can derive the weight of air lifted in unit time from the values of $v_f - v_a$ for each 50-mb layer (v_f being the mean belt speed, and v_a the wind component in the warm air). Assuming 80 per cent humidity before lifting, and ascent along the wet adiabatic through 10°C at 1,000 mb once saturation has occurred, we obtain from the tephigram the weigh of water released during lifting to the 700-mb level, and hence the average rainfall for the belt. This assumes that evaporation effects are negligible and that all the condensed wate reaches the ground as rain. Neither of these latter assumptions can be expected to hold in practice, so that the values we derive are probably overestimates. This computation for lifting from 1,000 to 700 mb gives a figure for rainfall of 1·8 mm, and for lifting to 500 mb (the average height of radar echo tops in Table 2), 3·5 mm. Rainfall of this order is reasonable for cold-front type precipitation belts in southern England, and is, we suggest a further indirect check on Fig. 2.

Marshall (1953) in Canada has produced evidence in the case of snow trails for the existence of compact generating elements which directly control precipitation movement at the ground, but where there is growth of precipitation throughout a considerable height

nge, as it is reasonable to think was the case in our belts, the movement cannot be con-olled in this simple way, and there seems to be little hope of relating it directly to the owth process.

On the assumption that the average wind components we have derived are typical conditions in belts of this kind (we have seen that they can be interpreted as subsidence hind the belts and lifting of the overtaken air, in accord with experience), it would seem at the level at which the mean wind speed across the belts equals the mean belt speed, hich we can think of as a level of non-divergence, can be regarded as the effective teering level.' The work of Ligda (1953) and the present study both suggest that this teering level' is close to the 700-mb level, and we think there is strong support for a le of forecasting that belts of precipitation of cold-front type move with a speed equal the component of the 700-mb wind across them.

Acknowledgment

We are glad to record the encouragement given us by Mr. R. F. Jones, who originated is study at East Hill. The paper is published with the permission of the Director-eneral of the Meteorological Office.

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On the characterization of tropical rainstorms in relation to runoff and percolation

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(Manuscript received 12 July 1957, in revised form 23 January 1958)

Summary

The statistical characterization of tropical rainstorms is considered. Linear relationships are demonstra between log duration and rate, and between log amount and rate.

The fate of rainfall when it reaches the ground is then considered, and it is shown that from the lin regression of amount of rain and rate, together with runoff data, percolation rates can be estimated. T consistency of estimates of percolation rate is demonstrated from data from Namulonge, Uganda, and fr the Ozark Highlands in Arkansas.

1. Introduction

The importance of rate of rainfall in determining its fate when it reaches the grou is evident to anyone who has watched a tropical storm. The measurement of rate, howeve is not very satisfactory with the standard instruments, designed and calibrated wi temperate rainfall conditions in view. An instrument has been designed to record rainf rates in tropical storms (Farbrother 1951) and has now been in use at Namulonge f six years. From the data accumulated the existence has been demonstrated of importa characteristic relationships between intensity, duration, and amount of rain in a storr It will be shown that these relationships can be used to eliminate the effect of differenc in intensity and duration of storms on runoff and percolation data.

Three instruments were used to provide the data from which the characteristics rainstorms at Namulonge were determined :

(*a*) *The standard raingauge.* This gave a record of the total amount of rain per storr

(*b*) *The Dines recording raingauge.* This gave a record of the duration of a storm A figure for rate may theoretically be calculated from the tangent of the lines on t chart. At tropical intensities the line is so nearly vertical that no useful figure can b derived, and moreover the lines representing successive fillings of the float chamber a so close together that at the higher intensities they cannot always be distinguished.

(*c*) *The Farbrother rate recorder,* which records instantaneous rate on a chart of t type illustrated in Fig. 1. The relation between rate and height on the chart is not linea but calibration is straightforward (Farbrother 1951).

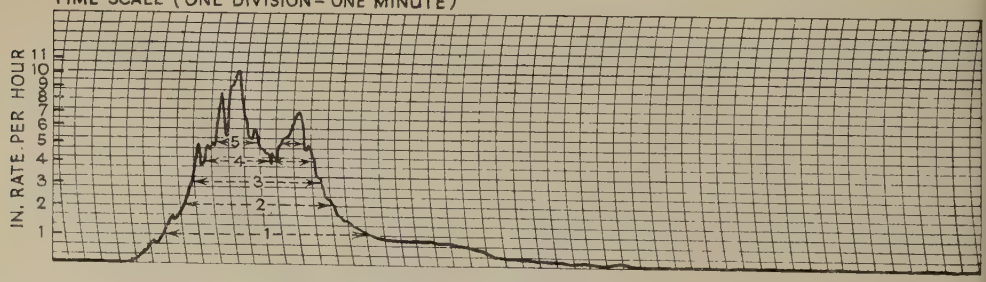

Figure 1. Farbrother rainfall-intensity record chart for a typical storm.

TABLE 1. PEAK RATE AND QUANTITY OF STORMS FROM JAN. 1950 TO DEC. 1955

ate n./hr	Quantity 0-0·25	0·26-0·50	0·51-0·75	0·76-1·00	1·01-1·25	1·26-1·50	1·51-1·75	1·76-2·00	2·01-2·25	Total
3-14	–	–	–	–	–	1	–	–		1
2-13	–	–	–	–	–	–	–	–	–	–
1-12	–	–	–	–	–	–	–	–	–	–
0-11	–	–	–	–	1	–	–	1	–	2
9-10	–	–	–	1	–	–	–	–	–	1
8-9	–	–	–	–	–	–	–	–	1	1
7-8	–	–	–	1	–	–	–	–	–	1
6-7	1	3	–	1	1	–	1	1	–	8
5-6	2	3	4	3	3	1	3	–	1	20
4-5	1	14	9	5	3	1	3	3	1	40
3-4	12	18	9	4	3	–	1	1	–	48
2-3	39	31	10	4	2	2	–	–	–	88
1-2	62	26	4	2	–	–	–	–	–	94
0-1	178	6	2	–	–	–	–	–	–	186
	295	101	38	21	13	5	8	6	3	490

2. THE CLASSIFICATION OF SINGLE STORMS

Data for peak rate, and for periods (in minutes) during which rain fell at rates in excess of 1 in., 2 in., 3 in./hr were computed from charts of individual storms. In Table 1 are given data for the majority* of storms experienced over the period January 1950 to December 1955, classified by total amount per storm and peak rate. It will be seen that there is a relationship between amount per storm and peak rate. The least squares fit may be expressed by the regression of instantaneous peak rate (Y) on the amount of the storm (X) in the regression equation

$$\log Y = 0{\cdot}47 \log X - 0{\cdot}26$$

for which the goodness of fit is demonstrated by $p < 0{\cdot}01$.

This generalized relationship is of course positive, but the variation is such that in spite of the statistical significance, it is not possible to predict peak rate from amount for any specific storm.

TABLE 2. CONTRIBUTION OF STORMS OF DIFFERENT SIZES TO TOTAL RAINFALL, JAN. 1950 TO DEC. 1955

Classes (in.)	Frequency	Total per class	Cumulative totals	Per cent of total Class	Cumulative
0·01-0·25	295	38·35	38·35	22·4	22·4
0·26-0·50	101	38·38	76·73	22·4	44·8
0·51-0·75	38	23·94	100·67	13·9	56·7
0·76-1·00	21	18·48	119·15	10·8	69·5
1·01-1·25	13	14·69	133.84	8·6	78.1
1·26-1·50	5	6·70	140·74	4·0	82·1
1·51-1·75	8	13·04	153·78	7·6	89·7
1·76-2·00	6	11·28	165·06	6·6	96·3
2·01-2·25	3	6·39	171·45	3·7	100·0
	490				

* A few records were incomplete or spoiled, owing to technical faults.

The contributions of storms of different amounts to total rainfall are of interest. I Table 2 are given a frequency array of storm size, the amount of rain which fell in storm in each frequency class, and cumulative totals of amount in successive classes. Abou 60 per cent of the rain fell in storms of 0·76 in. or less, and only 4 per cent fell in storm in excess of 2 in. More than half the storms yielded less than 0·25 in. of rain, and onl 7 per cent of all storms yielded more than 1·00 in.

The pattern of rainfall intensity may be examined by dividing the Farbrother recorde charts into successive intensity groups (intervals of 1 in./hr were chosen), and plottin against the number of minutes during which intensity equalled or exceeded that amount 16 storms were chosen at random from the group of storms in which peak intensit equalled or exceeded 2 in. per hour. Naturally for the whole duration of the storm th rain fell at an intensity greater than zero per hour, and rain fell at the peak rate fo 0 minutes. These two points, therefore, provide the two end points of the curve o duration against intensity. If log duration is plotted against intensity, the relationship i approximately a straight line for each individual storm. The regression equations for the 16 storms together with R^2 (coefficient of determination) for each are given in Table 3.

TABLE 3. Relation between log duration (y, in tenths of minutes) and rate (x, in inches per hour) in the form $\log_{10} y = a + bx$

Date	Quantity	a	b	R^2
25.4.53	0·29	2·57	− 0·43	0·85
20.7.53	0·56	2·82	− 0·56	0·88
24.3.53	0·71	3·01	− 0·66	0·72
22.4.53	0·79	3·03	− 0·50	0·96
21.8.53	0·85	2·59	− 0·33	0·98
27.5.52	0·88	3·29	− 1·16	1·00
26.4.53	0·93	3·34	− 0·62	0·82
18.10.51	1·00	3·19	− 0·62	0·84
27.4.52	1·15	2·98	− 0·44	0·71
16.4.52	1·20	3·02	− 0·46	0·95
14.4.53	1·34	3·59	− 1·19	0·89
4.4.52	1·67	3·40	− 0·67	0·94
1.4.52	1·70	3·43	− 0·86	0·97
2.11.51	1·76	3·36	− 0·69	0·88
4.5.53	1·95	3·12	− 0·42	0·95
15.9.53	2·24	3·03	− 0·29	0·91

The linear regressions accounted for all but a small part of the variation. The b coefficients differed quite considerably from storm to storm, varying from − 0·29 to − 1·19. This infers that storms with a low b coefficient were short with a high peak rate, and those with a high b coefficient were long with a low peak rate.

3. The characterization of seasons and years

Seasonal variation in storm pattern was studied by summing for each month the number of minutes at and above each intensity interval. Then the regressions of log duration on intensity were calculated for the first and second rainy seasons separately, for the years 1951, 1952 and 1953. March, April and May were taken as the first rainy season, and September and October as the second. In November, the number of storms which occurred in two of the three years was so small that it seemed desirable to omit that month from consideration. For the same reason May 1953 was omitted, there having been only three storms with a peak rate over 0·4 in./hr. Regression coefficients for the individual months and for the totals are given in Table 4.

TABLE 4. REGRESSION COEFFICIENTS OF LOG DURATION ON INTENSITY BY MONTHS FOR FIRST AND SECOND RAINY SEASONS

First rains		Second rains	
Month	b	Month	b
March 1951	− 0·51	September 1951	− 0·61
April 1951	− 0·71	October 1951	− 0·66
May 1951	− 0·66	September 1952	− 0·51
March 1952	− 0·78	October 1952	− 0·64
April 1952	− 0·51	September 1953	− 0·29
May 1952	− 0·93	October 1953	− 0·37
March 1953	− 0·63		
April 1953	− 0·53		
Overall	− 0·64	Overall	− 0·42

The overall regressions lines are plotted in Fig. 2. It will be seen that despite the diversity in pattern between storms in any one period, in the second rainy season the rain tends to fall in shorter and more intense storms than in the first rainy season – a conclusion that is in conformity with general observation but for which hitherto no statistical support has been adduced.

A similar overall analysis may be done by years, using storms over the whole twelve months. Differences between months and between seasons are thereby hidden, but in any discussion of long-term trends, some assessment of differences between years is of great value. The same three years were analysed, and the b coefficients for log total minutes at or above each rate against rate, together with their appropriate R^2 figures, are given in Table 5.

TABLE 5. ANNUAL RATE/TIME CHARACTERISTICS FOR THREE YEARS' RAINFALL AT NAMULONGE

Year	b	R^2	Actual annual rainfall (in.)	Estimated annual rainfall (in.)
1951	− 0·76	0·98	60	63
1952	− 0·68	0·99	30	35
1953	− 0·36	0·93	42	41

The regression lines are plotted in Fig. 3. It will be seen that the relationship was essentially linear in each year. The pattern of rainfall as indicated by the relation between duration and peak rate was almost exactly the same in 1951 and 1952 despite a difference of almost 30 in. in total rainfall (Table 5). The relationship was very different in 1953,

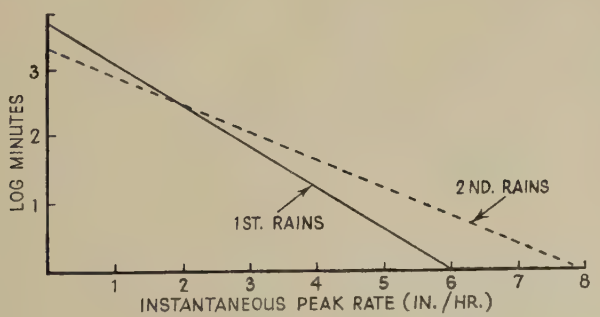

Figure 2. Characteristic rainfall of the two rainy seasons.

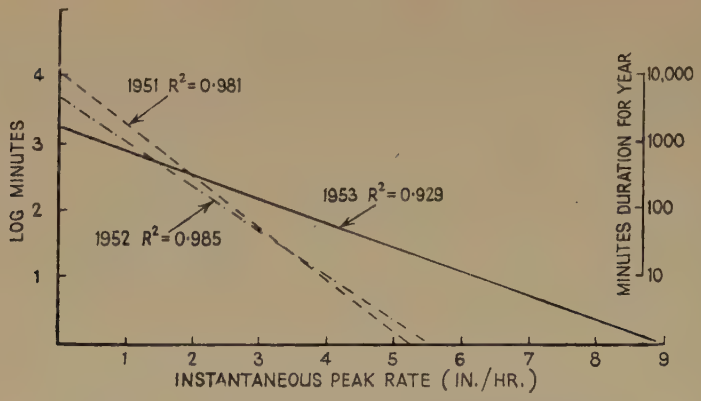

Figure 3. Rate/time characteristic of annual rainfall.

when the total rainfall was nearly midway between that of the other two years. Thus a very useful characterization of the annual pattern is possible. This may be checked by calculating back and estimating the annual rainfall. Actual rainfall and estimates calculated back from the regression lines are given in Table 5. Agreement was satisfactory. The slight positive bias in the estimates is due to the coarse grouping used in the calculation, particularly at the lowest rate.

4. The relation between rainfall characteristics and runoff and percolation

For agricultural purposes the relation between amount of rain and rate is of more direct relevance than that between duration and rate. The duration/rate relationship can, however, be converted to amount/rate by the use of the duration/rate regression and the figure for total amount. Thus the log amount/rate relationship must also be linear.

For a study of the relation between rainfall intensity and runoff, cumulative amounts at different rates were computed direct from the data from the Farbrother recorder and the standard 5 in. raingauge. Curves of log amount (cumulative totals) against rate for two of the 16 storms discussed above are given in Fig. 4. Considering now the rate of rainfall, the amount of water falling on the ground is divided into two parts, that which percolates into the soil, and that which runs off. On the log amount/rate diagram, therefore, the amount of runoff may be entered on the ordinate, and the percolation rate is then the point on the abscissa corresponding to the point at which the ordinate cuts the log amount/rate line.

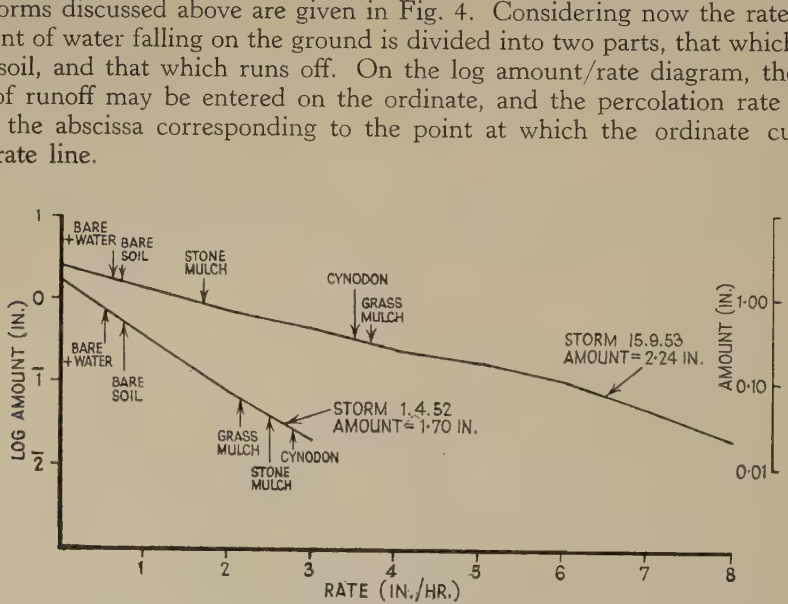

Figure 4. Log cumulative amounts against intensity for two storms.

It is necessary at this point to consider the assessment of runoff. In soil conservation actice, runoff is a function of the size of the land unit on which the water falls. The noff from a square plot an acre in extent may be proportionately more, or less, than that om a square plot 1/100th of an acre in size depending on the topography, the nature the surface, and the permeability of the soil. In the study here reported an attempt as made in the first instance to estimate what might be called a basic runoff rate by taking ry small plots on a very small slope, with carefully controlled surface conditions. Plots ere circular, approximately 3 sq. yd. in area, and the surface was smoothed to a two r cent slope. Runoff for individual storms was measured for a number of surface treatents each in duplicate. The treatments were as follows :

1. Bare soil.
2. Bare soil to which an amount of water equal to the previous day's evaporation was added daily.*
3. Grass mulch to a depth of approximately 3 in. (elephant grass).
4. Stone mulch to a depth of approximately 3 in. (stones therefore 3 in. diameter or less).
5. Turf : *Cynodon* planted at the beginning of the first rains, 1951; full cover reached about July 1951.

he two storms illustrated in Fig. 4 were chosen to demonstrate the estimation of percotion rate.† Runoff rates from the five treatments were superimposed on Fig. 4. Estimates percolation rate for the various treatments were as follows :

	Percolation rate (in./hr)	
Date of storm	1.4.52	15.9.53
1. Bare soil	0·8	0·7
2. Bare soil watered	0·5	0·6
3. Grass mulch	2·3	3·7
4. Stone mulch	2·4	2·0
5. *Cynodon* turf	2·7	3·5

he storm on 1.4.52 reached a peak rate of 4 in/hr only, and at this peak rate runoff from ie treatments with high percolation rates was very small indeed and percolation rate as, of course, limited to the rate at which water was received. Hence the potentialities f the treatments with high percolation rates were only fully demonstrated in storms with igh peak rates and large total amounts. The cumulative amount/rate relationships for ie annual rainfalls in 1951, 1952 and 1953 are plotted in Fig. 5, and on these are recorded ie runoff/percolation relationships for the various surface treatments of the runoff plots those years. Runoff amounts and percolation rates are set out in Table 6. The ercolation rate under *Cynodon* in 1951 was low because of very low percolation rates in ie first rains before full cover was achieved. Percolation was better under any form of oil cover than through bare soil, and it appears that grass mulch was superior to stone ulch, and turf (once it was fully established) the best treatment of all. Agreement etween years in percolation rates was satisfactory, considering the gentle slope of the egression lines, particularly that for 1953, and demonstrates the consistent behaviour f the surface treatments in a way that is not evident from an examination of the runoff ecords.

* Evaporation measured in the Namulonge open-pan recorder (Hutchinson and Farbrother 1956).

† In all cases the estimate of percolation rate includes a fraction due to absorption. This may be appreciable if the soil was dry en the storm began.

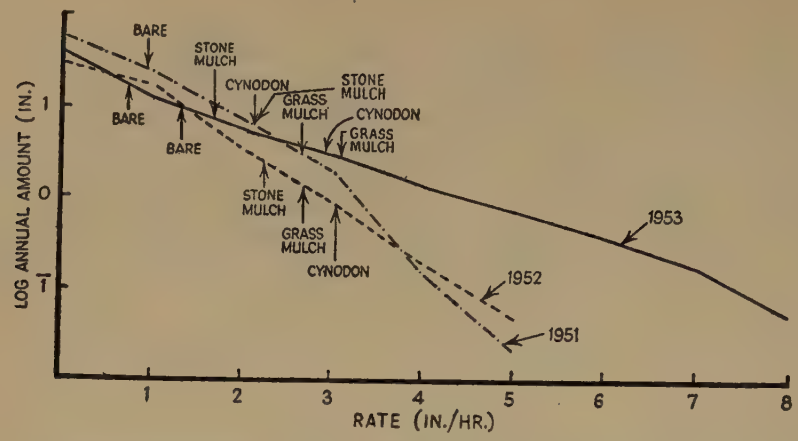

Figure 5. Cumulative annual totals of runoff for treatments and amount/rate characteristics for three yeaa

TABLE 6. ANNUAL TOTALS OF RUNOFF AND OVERALL PERCOLATION RATES (IN./HR) FOR SMALL PLOTS UNDD DIVERSE SURFACE TREATMENTS, 1951, 1952 AND 1953

	Rainfall (storms ⩾ 0·25 in.)	Bare soil		Grass mulch		Stone mulch		*Cynodon* turf	
		Runoff	Percolation	Runoff	Percolation	Runoff	Percolation	Runoff	Percolatid
1951	45·2	26·2	0·9	3·7	2·5	6·2	2·1	6·5	2·1
1952	24·9	10·4	1·3	1·6	2·6	2·0	2·3	0·8	3·0
1953	31·7	19·4	0·7	2·4	3·1	7·9	1·7	2·7	2·9

The simple log amount/rate characterization makes it possible to compare rainfaa behaviour under widely different climatic circumstances. Hood and Bartholomew (1956) have given data for amount and intensity of storms over a period of years in th Ozark Highlands in Arkansas, together with data for runoff from various surface treat ments. Their data may be converted into terms of average rates per hour, and the linea regression of rate on amount can then be calculated. Regressions for growing seaso totals (April to September) were plotted for each year from 1940 to 1948, and are repro duced in Fig. 6. The runoff percolation relationship for continuous cotton, rotation cotton and *Cynodon* (Bermuda grass) turf are set out on each regression line.

TABLE 7. SEASONAL RUNOFF TOTALS AND PERCOLATION RATES IN THE OZARK HIGHLANDS (FROM HOOD AND BARTHOLOMEW'S TABLE 7)

	Rainfall from which runoff occured (in.)	Continuous cotton (on contour)		Rotation cotton		Bermuda grass	
		Runoff (in.)	Percolation rate (in./hr)	Runoff (in.)	Percolation rate (in./hr)	Runoff (in.)	Percolatio rate (in./hr
1940	19·39	5·52	0·8	3·90	1·2	4·41	1·1
1941	18·12	5.67	1·0	2·13	1·8	0·89	4·6
1942	22·13	9·79	1·2	1·70	3·3	0·44	5·1
1943	17·68	7·78	1·0	4·57	1·6	0·21	4·4
1944	17·85	5·58	0·8	2·35	1·4	0·66	2·2
1945	37·38	19·39	0·4	11·56	0·8	1·51	3·2
1946	23·30	13·53	0·4	9·47	0·7	1·27	1·8
1947	11.56	2.70	1·7	1·38	2·0	0·09	5·3
1948	12·79	5·56	0·9	3·65	1·1	0·26	2·6

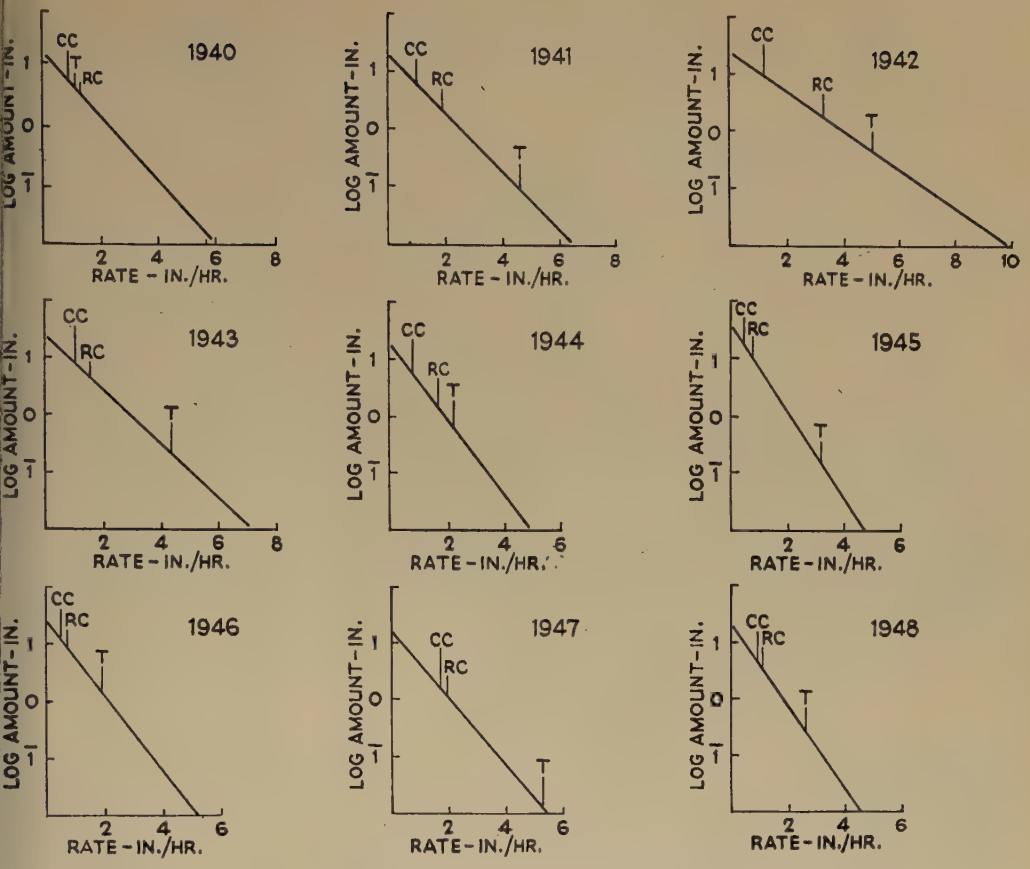

Figure 6. Characteristics of April to September rainfall in the Ozark Highlands.

Recorded figures for total runoff for each season, and mean percolation rates for the same seasons, as indicated on Fig. 6, are set out in Table 7. The experiment was started in 1940 on worked-out land that had been abandoned. The first crops of each treatment were associated with high runoff and low percolation rates, which must be regarded as reflecting previous history more than current treatment. In the next two years, percolation rates increased, and that under *Cynodon* greatly exceeded that under the arable crops. Percolation under rotation cotton exceeded appreciably that under continuous cotton on the contour. These differences in level persisted throughout the experiment. Percolation rates fell off from the peak in 1942 to a low level for all treatments in 1946. The decline occurred quite regularly, with the low rate under *Cynodon* in 1944 as the only anomaly. In 1947 all rates rose considerably, falling again in 1948, though not so low as in 1946. Inspection of the seasonal totals for rainfall from which runoff occurred shows that in the 1947 and 1948 seasons the totals were little more than half the total in the next lowest year. It may be suggested that under such circumstances the seasonal percolation rate might well be high, since there would be little likelihood of occurrence of periods of soil saturation, when the acceptance of further rainfall would be impaired.

Discussion

Comparing Figs. 5 and 6 it will be seen that peak rates of rainfall were of the same order at the two stations. The estimation of percolation rates was less precise at Namulonge. Trends in percolation rate that appear consistently in three surface treatments at the

Ozarks station would not be detected at Namulonge. Nevertheless, differences betwee surface treatments are consistent at both stations, and as between turf and a treatmen involving a large measure of exposure of the soil, the differences at the two stations wer of the same order.

The consistent behaviour of estimates of percolation rates is a matter of great import ance. It is usual in studies of the effect of cropping practices or soil treatments to measur susceptibility to erosion in terms of runoff. In view of the dependence of runoff on rainfal intensity, the use of percolation rate is to be preferred as an index of the effect of a surfac treatment. Moreover, it is on percolation rate that cropping treatments may be expecte to have their primary effect, and the provision of a simple technique for the estimation o percolation rates is therefore of great value in discussions of agricultural practices designe for moisture conservation. The technique may be carried further and used in connectio with catchment area studies to detect changes in overall percolation rates following the adoption of particular policies of catchment management. No very elaborate equipment is required, nor highly skilled observers. The standard raingauge is accepted as a basic requirement for all climatological studies and the Farbrother rate recorder can be made locally in the workshop.

The importance of direct estimates of rate of rainfall should be emphasized, particu- larly now that a simple relationship with amount has been demonstrated. The significance of intensity in determining runoff, and its effect on the amount of soil lost in erosion, is well recognized, but the measurement of the high intensities of tropical storms has not received the attention it deserves.

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Modification of the structure of a tropical cyclone on traversing a high plateau

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Summary

Apparent continuity is established between an Indian Ocean cyclone which reached the coast of southern rica and a disturbance which traversed the continent from east to west. The surface structure of the dis-rbance is established from autographic records of its passage over the Rhodesias and Nyasaland. The pressure ld is fitted to the ' normal ' vortex of James (1950) and the upper winds observed are in fair accord. The rface observations indicate the presence of broad belts of northwest and southeast winds with a fairly rupt transition but there is no evidence of fronts. Precipitation of the order of 50 mm per day is recorded er wide areas on several successive days. From consideration of the observed moisture content of the atmos-ere it is inferred that an inflow of the order of 2 m/sec in the lowest layers is required to account for the ecipitation. Elementary dynamic theory requires that such an inflow be accompanied by increasing circu-ion and deepening of the system. The depression, however, weakened and filled up slowly and it is shown at a reasonable allowance for turbulent and frictional losses would account for this.

1 Introduction

In the early part of the year tropical cyclones from the Indian Ocean frequently enter he Mocambique Channel and affect the weather on the mainland. Usually they move outhward down the Channel but occasionally they appear to move inland and such move-ents are accompanied by floods.

A tropical cyclone was observed passing from east to west to the north of Madagascar n 12-14 February 1950. It reached the coast of the mainland on 15 February when, nstead of recurving and proceeding down the Channel, it appeared to move inland. During the following week a well-marked depression traversed the continent from east o west and the passage was accompanied by strong winds and heavy rain causing loss of fe and much damage to property. The event was described briefly by Black (1950), nd Kreft (1953) described the passage from the synoptic point of view. Synoptic charts n the area affected are only available in daylight and only represent the pressure field pproximately, as the altitudes of the stations in the area vary from sea level to 1,500 m. On the other hand the disturbance traversed an area fairly well equipped with recording nstruments and this paper is largely devoted to an examination of the surface structure nd development of the disturbance as revealed by the records of these instruments.

A striking fact is that the disturbance weakened slowly during its passage over the ontinent but continued to give copious rainfall. The dynamical implications of this are xamined and it is suggested that the solution lies in the retarding effect of friction and urbulence on the winds in the lower layers.

2. Analysis of the pressure field

Kreft's (1953) charts show roughly circular isobars in the depression during its assage over the continent but the data are inadequate for a detailed study of the pressure eld. To obtain more detail the variation with time of station-level pressure at some 25 tations was analysed. Representative curves are reproduced in Fig. 1.

The curve for Antonio Enes is based on three observations per day plotted as recorde
That for Alto Moloque is based on two observations per day as recorded, except that t
pressure at 14 hr has been increased by 3 mb to allow for the diurnal pressure wa
The remaining curves are based on barograph records and represent the departure of t
pressure from the normal for the hour and the month. It has been shown by Sellick (194
that this form of representation eliminates the semi-diurnal wave almost completely, b
that the diurnal wave exhibits changes from day to day which remain as irregularitie

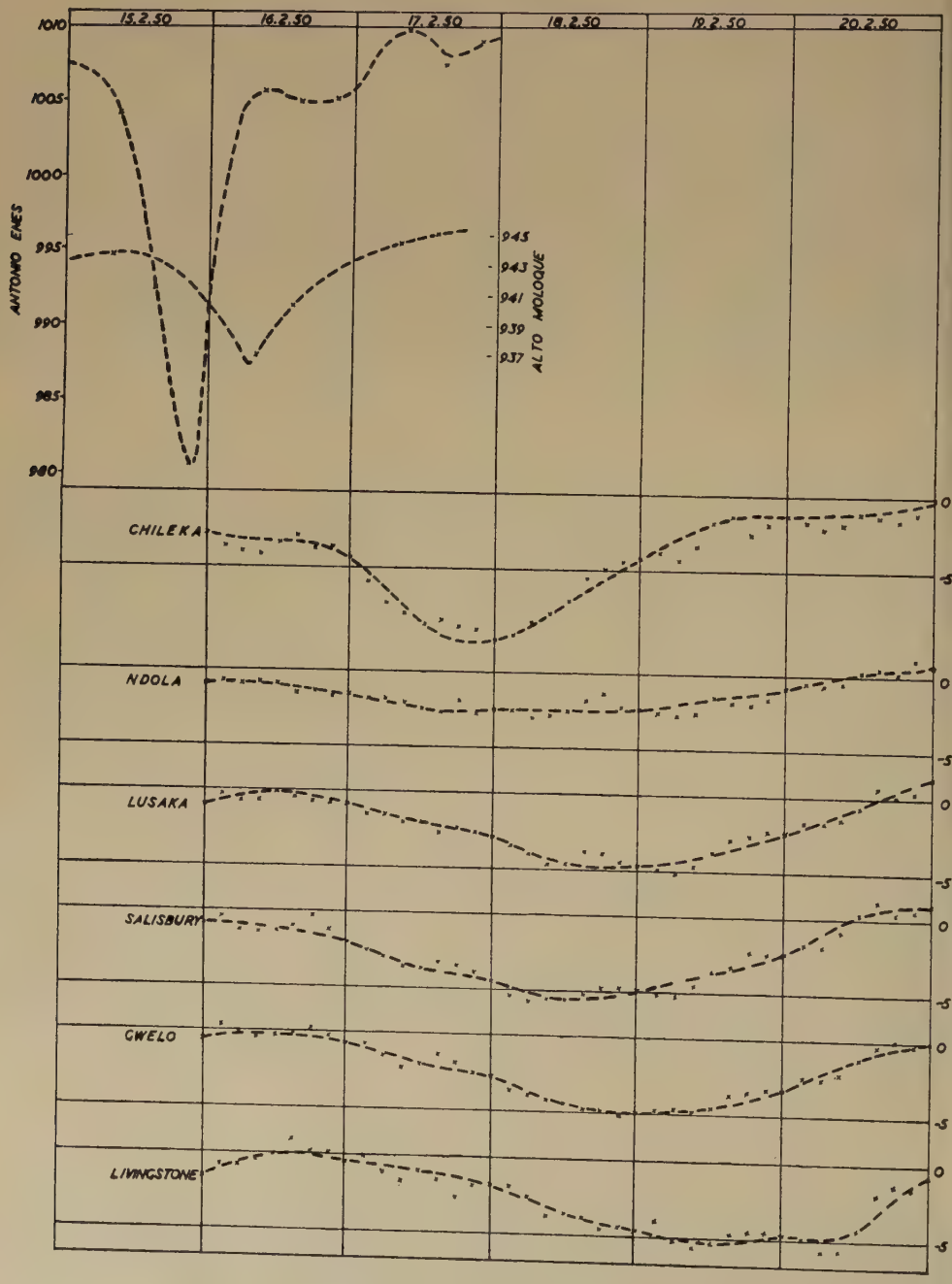

Figure 1. Variation of pressure.

uring the period under review the diurnal variation of temperature was abnormally small d was associated with a reduction in amplitude of the diurnal pressure wave. In conse- ience, the corrections applied are too large and a reversed diurnal wave appears in the otted points. To eliminate this while retaining the objectivity of the analysis, the rves have been drawn free-hand through the points at 12 hr and 24 hr at which the urnal wave has nearly zero amplitude.

The curve for Antonio Enes, a coastal station, is typical of a tropical cyclone and dicates a pressure field approximating to the vr = constant vortex. The curve for Alto oloque is based on inadequate data but suggests a vortex of the same type of greatly duced intensity. At Chileka the disturbance has broadened out very considerably and hibits a central area of great extent in which the vr = constant vortex certainly does not old. The curves for Salisbury, Gwelo, Ndola and Lusaka show a further spreading out the disturbance.

3. A MODEL OF THE PRESSURE FIELD

According to the synoptic charts prepared by Kreft the isobars of the disturbance ere nearly circular. A circular pattern greatly facilitates mathematical treatment and the ata were therefore examined to see whether the adoption of such a pattern could be stified. The greatest and most reliable information about the pressure field was recorded the disturbance passed through the line Ndola-Gwelo and a profile of the pressure nomaly due to the disturbance was constructed from the records at Ndola, Lusaka, alisbury and Gwelo. An attempt to fit a pressure profile based on the Rankine vortex as unsuccessful but the profile was found to fit James's (1950) 'normal' vortex fairly well.

$$p = 2 - 7{\cdot}8 \exp(-r^2/R^2) \quad . \quad . \quad . \quad (1)$$

here p is the pressure anomaly in millibars and R = 480 km.

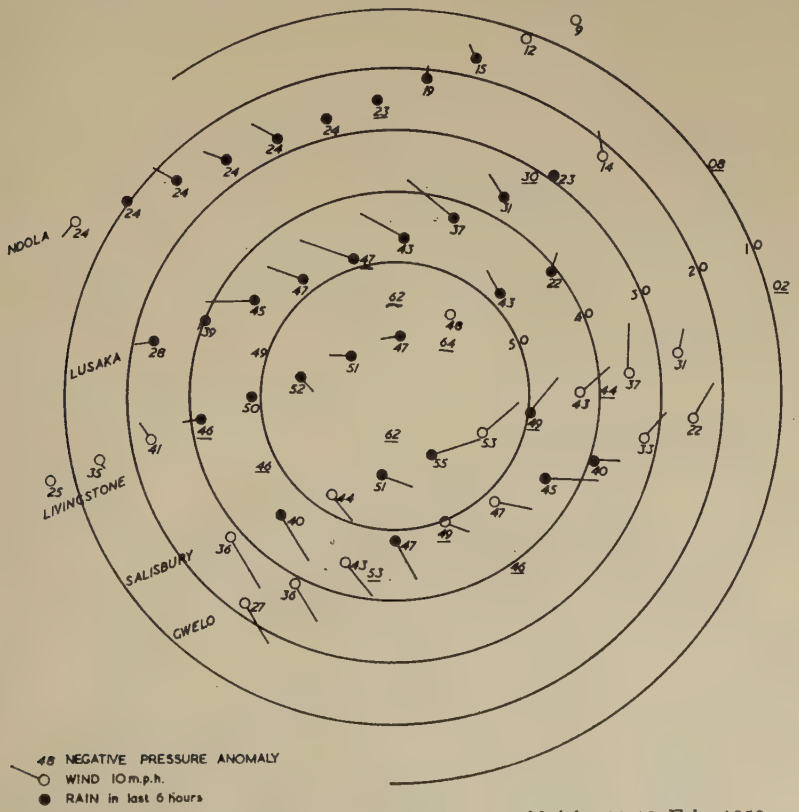

Figure 2. Reconstruction of the situation at midnight 18-19 Feb. 1950.

It was found that a symmetrical pressure field in accord with Eq. (1) reproduced t pressure fluctuations at the stations Ndola, Lusaka, Salisbury and Gwelo when mov across the area in a west-southwest direction at 8 kt.

4. Reconstruction of the pressure and wind fields

A reconstruction of the pressure and wind fields at midnight on the 18-19th w attempted and is shown in Fig. 2.

The lines of isanomaly of pressure are strictly in accord with Eq. (1). The observation at five stations, Ndola, Lusaka, Livingstone, Salisbury and Gwelo have been converte to space cross-sections at a velocity of 8 kt and are plotted on lines drawn through t stations parallel to the track of the disturbance. Winds are shown by lines of leng proportional to the velocity, rain in the past 6 hr by filling in the circles and pressu anomalies in tenths of a millibar. Pressure anomalies for midnight at these and certa other places are also entered on the chart for comparison and are underlined. The fit by no means perfect but, remembering that the figures were derived from barographs widely different levels, it is claimed that the assumed pressure field is reasonable.

Considering the surface winds, it is clear that a broad northwesterly current is swee ing in towards the rear and a southeasterly current is sweeping in to the left front quadran This conjunction of northwesterly and southeasterly currents is a common feature rainy spells but the pressure field normally has the appearance of a trough or col and close isobars are rare. The Livingstone anemometer, which is situated in the Zambezi valle about 300 m below plateau level, shows relatively poor agreement and the winds at Ndol are out of keeping with the gradient.

5. The track of the disturbance

The position of stations mentioned in the text and also the approximate position of th centre of the disturbance at various times as derived from the pressure data are show in Fig. 3.

After being reported north of Majunga on the morning of the 14th no further report of the position of the cyclone were received, but a disturbance was recorded at Antoni Enes on the evening of the 15th. The pressure changes at this station are consistent wit the passage of a cyclone, the direction and timing are consistent with the previous histor of the cyclone and there is no reason to doubt the continuity. During the passage of th trough Antonio Enes recorded winds of up to 48 kt backing from southerly to easterl indicating that the centre passed to the north. Hourly records at Mossuril, 175 km t the north-northeast, show the pressure falling and rising through 5 mb on the 15th an the winds veering from west to east. The evidence is that the cyclone passed inland slightl to the north of Antonio Enes.

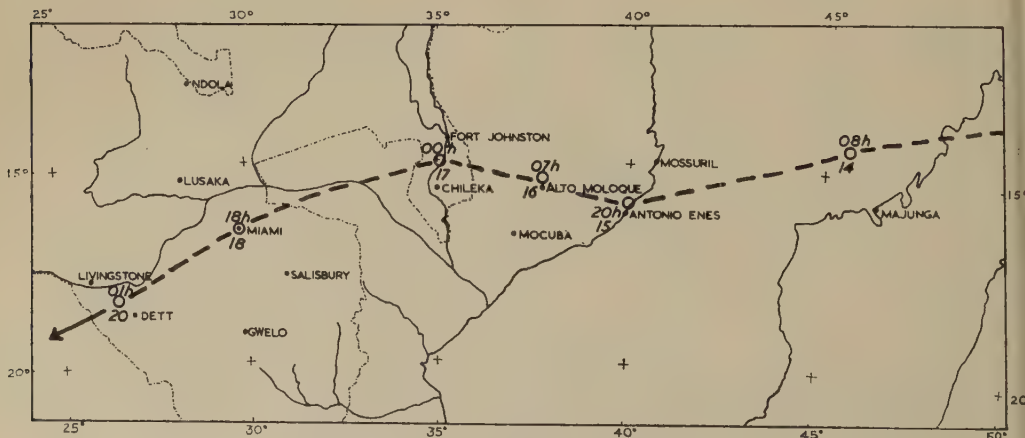

Figure 3. The track of the disturbance.

The next trace of the pressure disturbance is at Alto Moloque, 240 km west-northwest of Antonio Enes. A sharp trough was recorded with the lowest pressure at about hr on the 16th. The trough bears a family resemblance to that at Antonio Enes but is ery much shallower. The winds reported are very light and indefinite but are easterly luring and after the passage, indicating transit to the north of the station. The rate of ravel appears to be about 13 kt.

The disturbance entered Nyasaland and is recorded by very similar pressure curves t Chileka, Fig. 1, and at Fort Johnston. At Chileka the surface winds backed steadily hrough the night of the 16/17th from south to northeast. The centre appears to have passed between these stations shortly before midnight, giving an approximate rate of ravel of 9 kt. The trough has broadened but has retained its depth.

The path for the succeeding 48 hr lay in the Zambezi valley and records are only available on the flanks. The movements of pressure during this period are consistent with continued passage towards the west and the pressure trace at Miami shows the passage of a trough on the evening of the 18th. This represents a rate of travel of 7·5 kt. On very slight evidence the centre passed close to, and north of, Miami. The trough has broadened considerably and has lost about 2 mb in depth.

From this point the track is clearly indicated on records of a number of stations and the disturbance passed between Livingstone and Dett early on the 20th. This gives a rate of travel of 7 kt. The disturbance appears to have continued across Bechuanaland and South-West Africa. The continuity between the oceanic cyclone and the disturbance affecting the interior is thus fairly well established.

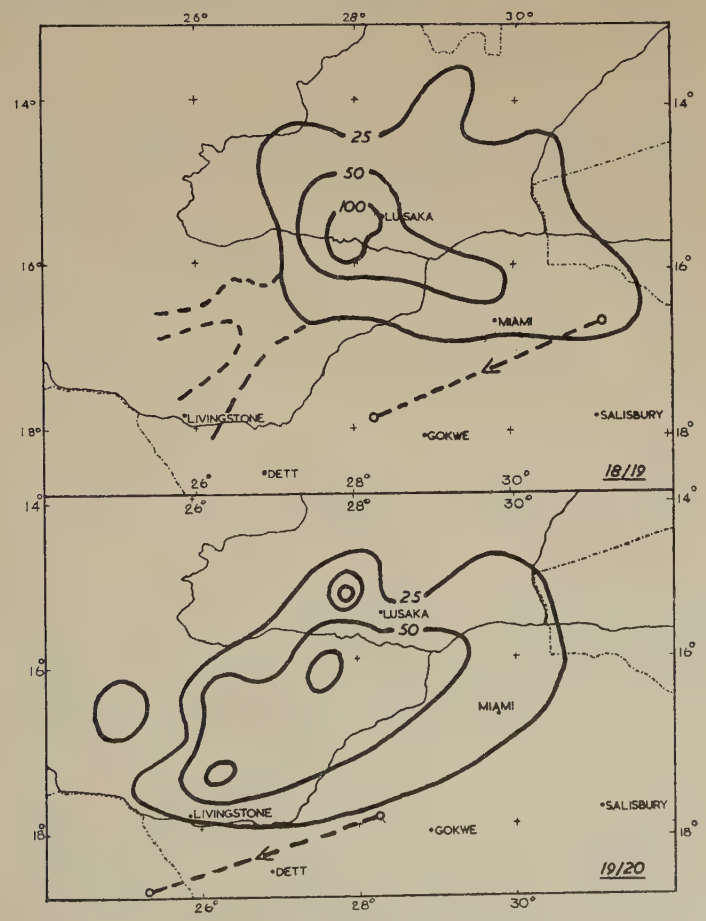

Figure 4. The rainfall.

6. The rainfall

Daily rainfall from available stations in Rhodesia and Nyasaland, as plotted and ana lysed by Kreft (1953), was examined. The first day's rainfall within the scope of th network was the 16th when many stations in central Nyasaland recorded from 100 t 200 mm. On the 17th the centre lay in the Zambezi valley. Heavy falls were distributea over a wide area, but the information is meagre. During the 18th and 19th the main area of rain was reasonably covered by the records. The areas receiving heavy rain on thes days are shown in Fig. 4 by isohyets of 25, 50 and 100 mm. Based on these two days i was computed that the daily fall averaged 52 mm over an area of 155,000 km^2.

The area over which rain was recorded was greater than this, but not all the precipita tion could be attributed to the disturbance. It was decided arbitrarily to confine attentio to the area included within the 25 mm isohyet and to exclude the area covered by a extension of this isohyet towards Livingstone on the 18/19th.

It is evident that the bulk of the rain fell on the right-hand side of the track. Earl on it was largely in the right front quadrant but it lagged to the rear on the 19th. N explanation is offered for these facts. Autographic records show rain for periods o 36 hr to 48 hr. At some stations the rain was continuous with varying intensity; at other in particular at Livingstone, the rain was intermittent and included bursts of over 20 mm per hour.

7. Upper winds

Weather was unfavourable for following pilot balloons. The meagre data available are presented in Table 1.

TABLE 1. Observations of upper winds

Station	Date/Time	Bearing	Distance	1,500 m			2,000 m			2,500 m		
		(deg)	(km)	*DD*	*VV*	$\dot{\theta}$	*DD*	*VV*	$\dot{\theta}$	*DD*	*VV*	$\dot{\theta}$
Lusaka	17/06	270	620	155	9	1·4	164	9	1·4	175	9	1·4
Gwelo	17/06	225	640	125	11	1·8	131	19	2·9	126	17	2·7
Salisbury	17/06	230	410	157	7	1·8	153	17	4·1	130	19	4·7
	17/17	220	270	148	9	3·3	142	14	5·1	120	16	5·9
	18/06	185	130	120	6	4·5	101	13	10·3			
Livingstone	18/06	255	580	100	3		90	7		100	3	
Chileka	18/06	75	410	15	19	4·5	360	32	7·7			
Ndola	17/06	295	640	230	3	0·4	225	5	1·5			
	19/06	5	530	347	11		297	13	2·5	294	17	3·2
	20/06	30	750	348	9		316	12	1·6	303	14	1·6

Velocities in m sec^{-1}

The station, date and time of observation and approximate bearing and distance from the centre of the disturbance are recorded. The observations are presented in the form of direction and velocity and, where the wind is nearly normal to the radius from the centre of the disturbance, the angular velocity about the centre is indicated.

The ground surface rises to 1,200 m on the plateau and exceeds this altitude in parts, hence 2,000 m may be taken as the free-wind altitude. At this level all winds other than that for Livingstone show directions roughly normal to the direction of the centre of the disturbance.

8. Upper-air temperatures and humidities

Radiosonde ascents were made daily in the mornings at Salisbury. The main features during the passage of the disturbance are shown in Table 2.

TABLE 2. SALISBURY RADIOSONDES

Date	17			18			19			20		
mb	*H* (gpm)	*T* (°C)	*W* (sp. hum.)	*H*	*T*	*W*	*H*	*T*	*W*	*H*	*T*	*W*
800	1,993	13·0	9·2	1,970	14·8	11·8	1,978	14·5	12·9	2,010	14·7	12·0
700	3,111	9·9	7·3	3,092	9·7	8·9	3,101	11·0	10·5	3,130	9·1	8·4
600	4,378	3·1	5·4	4,358	2·9	6·1	4,378	5·2	7·2	4,399	3·9	6·8
500	5,836	− 4·3	3·5	5,820	− 3·2	4·0	5,854	− 1·4	4·7	5,855	− 5·2	4·2
400	7,564	− 13·8	2·1	7,553	− 13·6	1·7	7,606	− 10·2	2·1	7,576	− 14·9	1·9
300	9,690	− 28·1		9,670	− 30·7		9,764	− 24·0		9,695	− 29·0	
200	12,466	− 49·8		12,431	− 51·3		12,589	− 48·6		12,465	− 53·6	
100	16,668	− 77·6		16,584	− 78·9		16,751	− 78·8		16,605	− 76·3	

There is an increase in moisture content from the 17th to the 19th and a recession on the 20th when the centre is well past. Apart from the 19th the heights of the isobaric surfaces vary in sympathy with the surface pressure and the total range of thickness from 800 to 400 mb is only 17 m, which is within the limit of accuracy of observation. The temperatures on the 19th are higher but are suspect. The whole system appears to have been moving slowly from east to west and the indicated contour altitudes on the 17th, 18th and 20th at all levels conform with this motion. If the logical picture of a slowly moving deep disturbance is correct, then the slopes of the upper contour surfaces to accommodate the observations on the 19th are unrealistic.

9. Surface temperatures

On the Rhodesian plateau during the rainy season surface temperatures exhibit a diurnal range of 15°F-20°F but the range is considerably reduced by cloud and rain. Comparisons are therefore difficult. During the passage of the disturbance all stations showed marked reductions in range which, in the rain area, fell as low as 5°F. Mean temperature for the 24 hr ending at 11 hr and 23 hr was computed and curves were drawn. These curves showed that at stations in the east there was a fall and rise in temperature broadly coincident with the pressure movements. Further to the west the temperature movement lagged up to 24 hr behind the pressure. This is closely in time with the rain and may be attributed to the conditions accompanying the rain.

10. Rainfall and moisture available

Adopting the figures derived above, the average daily fall over 155,000 km^2 was 52 mm and precipitation of this order persisted for four or more days. Based on local observations, evaporation and transpiration may have returned about 5 mm per day to the atmosphere, leaving an amount of 47 mm per day to be accounted for.

The specific humidity in the atmosphere over Salisbury during wet spells does not vary greatly and the radiosonde ascent of 18 February was chosen as representative. Adding small amounts for unobserved values at high levels, the total water-vapour content of the atmosphere was 3·58 gm in a column of 1 cm^2 cross-section. Comparing this with the average rate of precipitation it is clear that the circulation must have been such as to renew the air over the rain area at a rapid rate.

For the purpose of calculation the rain area is taken to be circular with a radius of 220 km. To produce rain at the rate recorded and to conform with the practically unchanging surface pressure pattern, it is necessary to provide for rather more than a complete change of air each 24 hr in a cylinder of 220 km radius extending from the surface of the earth to a great height without any increase or decrease in the amount of air in the cylinder. The air must enter in the lower layers and depart in the higher layers.

To deal with an inflow and outflow through the walls of the cylinder and circulation about the axis it is convenient to adopt a system of cylindrical co-ordinates about a vertical axis coinciding with the axis of the cylinder. In these co-ordinates z is vertical distance r is the distance of a point from the axis measured radially and θ, measured anti-clockwise is the horizontal angle subtended by the radius to the point and a fixed radius, l is the Coriolis parameter. Velocities in the direction of z are indicated by w but Newtonian notation is used for velocities and accelerations in the direction of r and θ.

Some pattern must be assumed for the inflow and outflow. The pattern

$$\rho\dot{r} = a \cos bz \quad . \quad . \quad . \quad . \quad (2$$

was adopted. $\rho\dot{r}$ is the horizontal momentum, a a constant of the dimensions of momentum and b a constant of the dimensions L^{-1} and of a size such that $bz = \pi$ at the top of the outflow. This flow pattern includes a very large part of the water vapour in the inflow and very little in the outflow and maintains the mass of air within the cylinder constant. It was decided arbitrarily to take the base of the cylinder at the height of the 850 mb surface and the top at the height of the 200 mb surface.

If W is the specific humidity in g/kg, the amount of moisture entering or leaving through 1 m^2 of superficial area of the wall of the cylinder is $\rho\dot{r}W$ which is $Wa \cos bz$ where a is in kg m^{-2} sec^{-1}. The results of the calculations appear in Table 3.

TABLE 3. MOISTURE EXCHANGE

mb	ΔH (m)	W (g kg^{-1})	$W \cos bz$		$\Delta HW \cos bz$
850		14·6	14·6		
	519			13·1	6·80
800		11·8	11·7		
	546			10·9	5·95
750		10·6	10·2		
	576			9·1	5·25
700		8·9	7·9		
	613			6·9	4·25
650		7·3	5·8		
	653			4·9	3·20
600		6·1	4·1		
	701			3·3	2·30
550		5·1	2·6		
	761			1·9	1·45
500		4·0	1·2		
	827			0·7	0·58
450		2·6	0·3		
	906			0	0
400		1·7	− 0·3		
	1,000			− 0·5	− 0·50
350		1·3	− 0·6		
	1,117			− 0·5	− 0·56
300		0·6	− 0·4		
	1,272			− 0·4	− 0·51
250		(0·4)	− 0·4		
	1,489			− 0·2	− 0·30
200		(0·2)	− 0·2		
				Total	27·91

The first column shows the millibar surfaces used in the calculations, the third column the specific humidity and the fourth column the relative rate of transport of moisture at the surfaces. The second column is the partial thicknesses between the surfaces, the fifth the average rate of transport of moisture in the layers and the last column is the rate of delivery of moisture through each linear metre of the circumference of the cylinder when the velocity is such that 1 kg of air per second enters through 1 m^2 of the

ll of the cylinder at 850 mb. The density of the air at this level is sensibly 1 kg m^{-3}, nce, from the table, 27·9 kg of moisture will be gained through each metre of the cumference every second when the inward velocity at 850 mb is 1 m sec^{-1}. The rate of in of moisture within the cylinder is then 2·19 g cm^{-2} of horizontal area per day and, suming that all condensed moisture falls as rain, the average precipitation would be ·9 mm per day. Thus a velocity of 2·14 m sec^{-1} at 850 mb would be required to maintain infall at the rate of 47 mm per day. As the flow pattern adopted is highly efficient in livering moisture and full allowance has been made for possible increments of moisture om the surface the velocity of inflow computed above is probably the minimum velocity pable of supplying the moisture to a circular area.

11. Dynamic development

From § 2 it is clear that the central pressure rose and the gradients weakened as e disturbance traversed the land. On the other hand, from § 10 it is clear that the supply moisture for the persistent rainfall could only have been obtained as a result of conver- nce in the lower layers of the atmosphere. Such convergence in frictionless flow must, the conservation of angular momentum, lead to increasing circulation on the rotating rth and would rapidly terminate the convergence unless accompanied by a steepening the pressure gradients. As the convergence must exist and the surface circulation and ressure gradients do not increase it is necessary to find some physical process to account r the failure of the circulation to develop. The answer appears to lie in the effects of iction and turbulence which can modify the circulation arising out of the conservation angular momentum without necessarily affecting the inflow.

12. Effect of friction and turbulence

In a circular symmetrical pattern the conservation of angular momentum on the otating earth may be expressed as

$$\frac{d}{dt}\{r^2(\dot{\theta}+l/z)\}$$

the notation of § 10. The rate of growth of the circulation is then

$$\ddot{\theta} = -\frac{\dot{r}}{r}(2\dot{\theta}+l) \qquad . \quad . \quad . \quad . \quad (3)$$

he effect of friction and turbulence may be expressed as a rate of loss of kinetic energy the circulation

$$\tfrac{1}{2}c\rho r^2\dot{\theta}^2$$

here c is the rate and of dimensions T^{-1}.

The rate of change of kinetic energy due to the conservation of angular momentum is

$$\frac{d}{dt}\tfrac{1}{2}\rho r^2\dot{\theta}^2$$

nd, treating ρ as sensibly constant for horizontal motion and substituting for $\ddot{\theta}$ from q. (3) above

$$\frac{d}{dt}\tfrac{1}{2}\rho r^2\dot{\theta}^2 = -\rho r\dot{r}\dot{\theta}(\dot{\theta}+l)$$

hich may be combined with the frictional term to give

$$\rho r\dot{\theta}\{\tfrac{1}{2}cr\dot{\theta}-\dot{r}(\dot{\theta}+l)\}$$

nd there will be no change in $\dot{\theta}$ when

$$\dot{r} = \frac{c r \dot{\theta}}{2(\dot{\theta} + l)}$$

Lastly, assuming that the change of r with time may be neglected, the angular veloc due to a symmetrical pressure field may be found from

$$r\dot{\theta}(\dot{\theta} + l) = \frac{1}{\rho}\frac{\partial p}{\partial r}$$

Using the pressure field in § 3, taking $\rho = 10^{-3}$ g cm^{-3} and $l = -4{\cdot}03 \times 10^{-5}$, valu appropriate to the plateau and latitude 16°S, the angular velocity has been compute From the angular velocity the rate of flow for steady conditions was computed from Eq. c is the proportion of kinetic energy lost per second. Haurwitz (1941) and Brunt (193 discuss the rate of dissipation of kinetic energy. Using the former's Eq. (89·5) the rate 16° lat. would be $1{\cdot}6 \times 10^{-5}$ sec^{-1}. A value derived from the latter's figures is 6×10^{-5} sec in the layer between the ground and one kilometre. For the purposes of this paper t value of 4×10^{-5} sec^{-1} was adopted.

The circulatory velocity was also computed and, from the rates of inflow, the diver ence in each annular ring of 100 km width was found.

TABLE 4. ELEMENTS OF A NORMAL VORTEX WITH ALLOWANCE FOR FRICTION AND TURBULENCE

r	$-\dot{\theta} \times 10^5$	$-\dot{r}$	$-\theta r$	$-\dot{r}r$	Div $\times 10^5$
0	4·15	0	0	0	
					− 2·02
100	4·07	1·01	4·1	1·01	
					− 1·96
200	3·91	1·97	7·8	3·94	
					− 1·83
300	3·63	2·84	10·9	8·51	
					− 1·65
400	3·26	3·58	13·0	14·30	
					− 1·45
500	2·85	4·15	14·3	20·80	
					− 1·36
600	2·40	4·48	14·4	27·80	
					− 0·61
700	1·96	4·58	13·7	32·10	
					− 0·40
800	1·52	4·39	12·2	35·10	
					− 0·04
900	1·13	3·94	10·2	35·40	
					+ 0·22
1,000	0·80	3·33	8·0	33·30	

The results appear in Table 4. Comparison of the angular velocities with the observe values in Table 1 shows fair agreement at radii beyond 500 km but the observed valu at short radii are greater. The high value for Chileka is difficult to explain but that f Salisbury may be due, in part, to an error in the estimated distance of the centre. Accordin to the values in Table 4 the inward inclination of the wind varies from about 13° at 100 k to 23° at 1,000 km. Apart from Lusaka and Gwelo which show outward component the remaining winds at 2,000 m show inward components ranging from 6 to 22° and th larger components are at the greater radii.

The divergence computed from the steady flow pattern is in good agreement with tha computed from the rainfall and moisture content of the air but the flow pattern require a very slow fall off in convergence up to a radius of over 800 km and divergence thereafte This is contrary to the observed rainfall which shows a high concentration of rain over relatively small area and no rain attributable to the disturbance beyond radii of the order o 4-500 km.

13. Conclusions

The evidence favours the conclusion that the disturbance which passed over the land ea between 16-21 February was continuous with the tropical cyclone previously observed the Indian Ocean.

The observed pressure and wind field when the disturbance passed through the hodesias shows a reasonably good fit with James's ' normal ' vortex and the stabilization the development over the land occurred at a level not inconsistent with a reasonable lowance for losses by friction and turbulence. On the other hand, the model shows oteworthy differences from the observed events, in particular in the distribution of ecipitation.

14. Acknowledgment

The assistance of the Director of the Mocambique Meteorological Service in supplying anuscript data is gratefully acknowledged.

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The relation between Eulerian time and space spectra

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SUMMARY

Simultaneous observations of space correlations and time correlations verify that Taylor's hypothe $x = Ut$ is valid for intervals up to at least 90 m, and for relative intensities of turbulence at least up to 0·2 It is also shown that, when the stratification is stable, the longitudinal scale of turbulence tends to be mu larger along the flow than across it. In an unstable layer, the scale is of the same order of magnitude in directions.

1. INTRODUCTION

Eulerian space spectra of atmospheric velocity components are of importance to designe of aircraft and other structures. Further, the theory of space spectra is relatively well understoo On the other hand, we have considerable observational evidence of time spectra, particular in the lower portion of the atmosphere (see, for example, Panofsky and McCormick 1954; Suor 1957; Deland and Panofsky 1957; and Jones 1957). In fact, the point has almost been reache where accurate estimates of time spectra in the lowest 100 m can be made, given measures of th stratification of temperature, the wind speed (or wind shear), the roughness of the ground, an the elevation. In order that this information be useful in engineering applications, the relatic between time and space spectra, or their Fourier transforms, the time and space correlatic functions, needs to be understood.

G. I. Taylor (1938) stated that space and time spectra and correlation functions are equiva lent, provided that the 'level' or 'relative intensity' of turbulence, $b = \frac{\sigma_u}{U}$ is sufficiently lo Here U is the mean wind speed, and σ_u the root-mean-square deviation of the turbulent veloci component in question. Under Taylor's hypothesis, a space correlation function in the directio of the mean wind x can be determined from the time correlation function by replacing tim t by x/U. Similarly, the space spectrum in the direction of the mean wind, x, can be found b replacing the frequency n by Uk, where k is the wave number.

Taylor's hypothesis has been verified experimentally in the wind tunnel by Favre, Gavigli and Dumas (1955) where the level of turbulence is considerably lower than normally in th atmosphere. R. J. Taylor (1957) confirmed the equivalence of x and Ut for the inertial subrang in the atmosphere; at the other extreme, with eddies the size of cyclones, G. I. Taylor's hypothesi does not seem to be valid (Hutchings 1955).

On the theoretical side, Gifford (1956) extended a theory by Ogura (1953) to show tha Taylor's equivalence of x and Ut should apply provided only that the level of turbulence is les than unity. Taylor's hypothesis should therefore be correct under conditions normally existin in the atmosphere. This paper presents an observational test of this conclusion.

2. INSTRUMENTATION AND DATA REDUCTION

The observations discussed in this paper were made by H. E. Cramer and H. C. Vaughan o the Massachusetts Institute of Technology during an extensive series of diffusion experiment sponsored by the Air Force Cambridge Research Centre at a field site near O'Neill, Nebraska during the summer of 1956. Sensitive bivanes and heated-thermocouple anemometers wer used to measure wind speed, azimuth and elevation angle at five points along either a north-sout or east-west line of orientation. Sensing elements were at a height of 2 m above the ground an separation distances between the points of measurement were 6, 12, 24, and 48 m respectively Data were recorded on high-speed chart recorders for periods of 20 min; characteristic times o the instruments are approximately 0·5 sec or less for the wind speeds occurring during the obser vation periods cited in the paper. The instrumentation is described by Cramer, Gill and Recor (1954). Data were abstracted from the chart records at intervals of 1·066 sec and entered on punc

ards by R. M. Stewart, Jr. at Iowa State College by means of automatic equipment. From the ards, turbulent velocity components u, v, and w, (referred to a rectangular co-ordinate system with x along the mean wind direction) and various auto-correlation functions, cross-correlation unctions, spectra, and cross-spectra were determined by means of an IBM 704 electronic computer ocated at the Lynn, Massachusetts plant of the General Electric Co. The data reduction was upervised by M. L. Barad and D. A. Haugen of the Air Force Cambridge Research Centre.

The terrain at the field site near O'Neill, Nebraska is unusually smooth (z_0 less than 1 cm, with an unobstructed upwind fetch of more than 1 km). Values of the mean wind speed used in his paper were obtained from measurements made by the Agricultural and Mechanical College of Texas and the Massachusetts Institute of Technology.

3. Test of homogeneity of spectra

Time-spectra of the various velocity-components were available at each of the five anemometer positions. The vertical-velocity spectra were judged unreliable, since their scale is so small that most of the energy occurs in periods less than the interval between observations. This can be seen by the fact that the auto-correlation function drops to nearly zero after one second. As a result, high-frequency energy is ascribed to lower frequencies, and the spectra are incorrect.

The spectra of each horizontal velocity component observed at the five positions were plotted on the same graph paper. Of the eight spectra plotted, only one showed an apparently systematic difference of one anemometer from the others; in the other cases, the variation between spectra was of a random character, although the variations were sometimes slightly larger than expected from Tukey's theory of sampling variations of spectra. Therefore it was decided to consider the turbulence sufficiently homogeneous to proceed with the test of Taylor's hypothesis.

4. Comparison between auto-correlation functions in space and time

The characteristics of the runs analysed are given in Table 1. It will be seen that in four of the runs the angle between wind and anemometer base line was less than 10°. The primary test of Taylor's hypothesis was based on these runs. For each of these periods the time-correlation functions at the five positions were averaged and plotted as function of the time lag. Space correlations could be obtained for 10 separations of observing positions, varying from 6 m to 90 m. These correlations are, however, not true space correlations; true space correlations would require correlations of simultaneous measurements at many positions equidistant from each other. Standing waves, if present, would not influence the cross correlation in time between the velocity components measured at two stations a distance x apart. However, the presence of such waves would make itself felt on true space correlations. The space correlations obtained from observations at different times should be equivalent to true space correlations, if the state of turbulence can be considered as stationary and homogeneous.

Fig. 1 shows the simultaneous space- and time-correlation functions for the u- and v-components for period 6, under the assumption that $x = Ut$. U was determined by averaging observations obtained by teams from the Massachusetts Institute of Technology and the Agricultural and Mechanical College of Texas.

TABLE 1. Conditions during observing periods

Run No.	Date 1956	Time (CST)	Angle ° between wind and anemometer line	Speed of mean wind, (m sec^{-1})	Level of turbulence
6	6 July	1655	4	6·7	0·16
7	10 July	1355	23	4·4	0·32
8	10 July	1655	90	4·6	0·25
10	11 July	1155	27	4·6	0·34
17	23 July	1955	8	3·4	0·16
21	25 July	2155	9	5·9	0·20
23	29 July	2055	36	6·1	0·18
24	29 July	2255	40	5·9	0·18
32	6 August	1955	9	2·2	0·26
35S	7 August	2255	49	4·0	0·18
39	13 August	2225	54	2·5	0·29

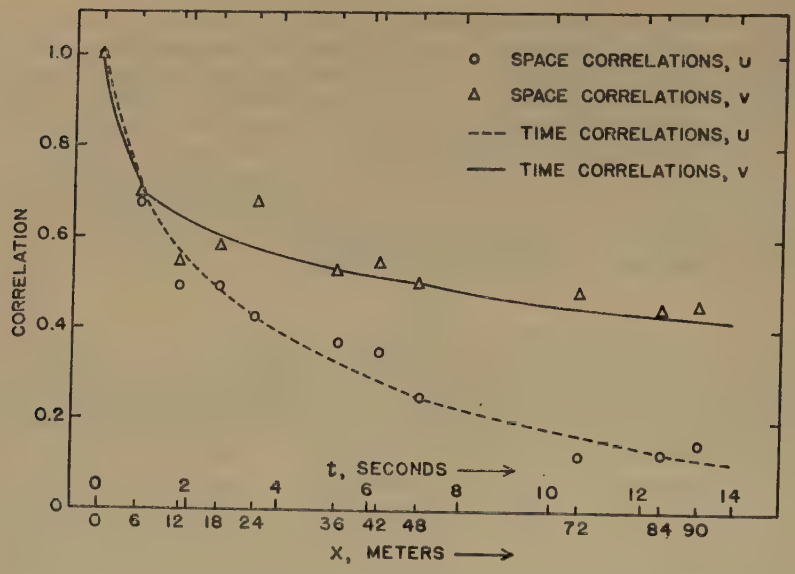

Figure 1. Time and space correlations for u and v, Run 6. Time correlation curves are drawn through five-anemometer averages every 1·066 sec.

The agreement between space- and time-correlation is probably as good as can be expected. The space-correlation coefficients show considerably more scatter than the time correlations, partly because the time correlations have been averaged over five quantities each. There is certainly no indication that the eddies travel with a speed different from that of the wind. Further, the agreement does not deteriorate with increasing distance, at least within the observed range of distance.

The space and time correlations for all periods are tabulated in Tables 2 and 3. In these tables, measured space correlations are compared with interpolated time correlations under the assumption that $t = x/U$. Table 2 lists the results for periods in which the angle between wind and anemometer line is less than 10°. Table 3 lists the remaining results. The agreement in Table 2 is generally good. The only systematic differences appear at $x = 6$ m, where the space correlation is consistently less than the corresponding time correlation. It is believed that this small discrepancy is not due to a failure of the hypothesis that $x = Ut$. As a matter of fact, R. J. Taylor's observations have already confirmed G. I. Taylor's hypothesis for small time or space intervals. The difficulty is probably that the high-frequency extreme of the spectrum is most sensitive to observational difficulties.

Another test of the correctness of Taylor's hypothesis consisted in comparing the space spectra with the time spectra. The estimates of the space spectra fell within the range of the time spectra observed at the five observing stations. It is therefore concluded tentatively, that G. I. Taylor's hypothesis is valid over the range of distances studied at O'Neill, for levels of turbulence as large as 0·26. Only if standing waves existed, is this conclusion incorrect, since the analysis just presented would have been unable to detect such waves.

Subject to the hypothesis that $x = Ut$, we can now interpret the information in Table 3. Here, the columns computed from the time correlations represent space correlations in the mean wind direction; the space correlations, of course, apply to the line of the anemometers. The day-time observations show good to fair agreement between correlation functions in the different directions; in periods 23, 24, and 35S, however, all the correlation coefficients for the u-components drop off with increasing distance much more rapidly along a line at an angle with the flow than along the flow. This confirms a conclusion drawn from earlier work at O'Neill (Deland and Panofsky 1957): at daytime, the scales of turbulence are of the same order of magnitude along the wind as across the wind; at night, the scale along the wind is much larger than that across the wind. The v-components have about equally small scales along and across the wind. This is due to the fact that, at night, only the small, essentially isotropic eddies have cross-wind turbulent velocity components of considerable magnitude. Only in run 39, the scales remain large at night, owing to a gradual turning of the wind.

TABLE 2. SPACE CORRELATIONS r_x AND INTERPOLATED TIME CORRELATIONS r_t WHERE $t = x/U$
WIND WITHIN 8° OF ANEMOMETER LINE

	Run 6				Run 17				Run 21				Run 32			
, m	u		v		u		v		u		v		u		v	
	r_x	r_t	r_x	r_t	r_x	r_t	r_x	r_t	r_x	r_t	r_x	r_t	r_x	r_t	r_x	r_t
6	0·67	0·71	0·70	0·72	0·55	0·59	0·16	0·25	0·81	0·81	0·45	0·49	0·86	0·87	0·09	0·15
12	0·49	0·56	0·55	0·64	0·42	0·43	0·06	0·14	0·71	0·70	0·39	0·38	0·85	0·84	0·15	0·13
18	0·49	0·47	0·59	0·60	0·29	0·33	0·14	0·10	0·63	0·64	0·33	0·32	0·87	0·83	0·13	0·13
24	0·42	0·42	0·68	0·57	0·27	0·27	0·08	0·08	0·53	0·58	0·31	0·29	0·85	0·83	0·13	0·14
36	0·37	0·32	0·53	0·53	0·18	0·18	0·07	0·07	0·49	0·51	0·24	0·24	0·83	0·83	0·07	0·12
42	0·35	0·28	0·55	0·52	0·12	0·14	0·08	0·07	0·48	0·49	0·20	0·22	0·83	0·83	0·12	0·11
48	0·25	0·25	0·50	0·50	0·14	0·11	0·10	0·06	0·44	0·46	0·29	0·21	0·83	0·82	0·10	0·10
72	0·12	0·17	0·48	0·45	0·07	0·07	0·10	0·05	0·36	0·40	0·24	0·20	0·85	0·82	0·04	0·05
84	0·13	0·13	0·45	0·43	0·05	0·05	0·16	0·04	0·37	0·39	0·20	0·18	0·83	0·82	0·07	0·06
90	0·15	0·12	0·46	0·43	0·05	0·05	0·24	0·04	0·38	0·39	0·26	0·17	0·85	0·82	0·09	0·07

TABLE 3. SPACE CORRELATIONS r_x AND INTERPOLATED TIME CORRELATIONS r_t WHERE $t = x/U$
WIND DIRECTION DIFFERS FROM ANEMOMETER LINE DIRECTION BY MORE THAN 20°

	Run 7				Run 8				Run 10				Run 23			
, m	u		v		u		v		u		v		u		v	
	r_x	r_t	r_x	r_t	r_x	r_t	r_x	r_t	r_x	r_t	r_x	r_t	r_x	r_t	r_x	r_t
6	0·86	0·90	0·91	0·91	0·70	0·86	0·88	0·90	0·81	0·91	0·85	0·89	0·42	0·73	0·41	0·42
12	0·81	0·82	0·85	0·85	0 65	0 77	0 84	0 87	0 80	0·85	0·81	0·83	0·26	0·60	0·25	0·31
18	0·77	0·76	0·81	0·81	0·59	0·72	0·82	0·84	0·72	0·80	0·75	0·79	0·23	0·50	0·19	0·24
24	0·69	0·72	0·80	0·79	0·63	0·67	0·78	0·83	0·80	0·76	0·76	0·75	0·47	0·44	0·19	0·19
36	0·65	0·65	0·76	0·76	0·59	0·60	0·73	0·79	0·76	0·70	0·68	0·68	0·11	0·37	0·16	0·14
42	0·63	0·63	0·73	0·72	0·56	0·57	0·75	0·78	0·69	0·68	0·67	0·65	0·12	0·35	0·11	0·13
48	0·58	0·61	0·68	0·70	0·44	0·54	0·69	0·76	0·65	0·66	0·66	0·62	0·10	0·32	0·07	0·12
72	0·49	0·52	0·61	0·63	0·48	0·46	0·64	0·72	0·59	0·59	0·58	0·53	0·01	0·22	−0·04	0·07
84	0·46	0·48	0·56	0·71	0·44	0·43	0·63	0·70	0·54	0·54	0·59	0·50	0·05	0·21	0·01	0·06
90	0·45	0·44	–	0·60	0·42	0·41	0·65	0·69	0·51	0·52	0·54	0·48	0·04	0·18	0·05	0·07

	Run 24				Run 35S				Run 39			
x, m	u		v		u		v		u		v	
	r_x	r_t	r_x	r_t	r_x	r_t	r_x	r_t	r_x	r_t	r_x	r_t
6	0·33	0·72	0·41	0·43	0.33	0·55	0·33	0·22	0·85	0·88	0·82	0·82
12	0·28	0·56	0·24	0·28	0·37	0·46	0·23	0·21	0·85	0·85	0·86	0·80
18	0·07	0·46	0·18	0·22	0·33	0·42	0·17	0·20	0·86	0·84	0·83	0·80
24	0·13	0·24	0·19	0·16	0·37	0·39	0·24	0·20	0·84	0·84	0·83	0·79
36	0·06	0·28	0·09	0·12	0·44	0·34	0·27	0·19	0·83	0·83	0·79	0·79
42	0·05	0·24	0·10	0·10	0·30	0·33	0·23	0·19	0·86	0·83	0·76	0·78
48	0·06	0·20	0·06	0·08	0·36	0·32	0·24	0·18	0·83	0·83	0·74	0·78
72	0·01	0·12	−0·04	0·06	0·37	0·32	0·17	0·16	0·84	0·81	0·79	0·77
84	−0·07	0·10	0·01	0·05	0·41	0·33	0·23	0·17	0·83	0·80	0·75	0·77
90	−0·08	0·08	0·05	0·04	0·33	0·32	0.16	0.17	0·85	0·80	0·73	0·76

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Atmospheric pollution by hydrochloric acid

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(Manuscript received 6 March 1958)

SUMMARY

Precipitation samples from urban deposit gauges in Britain exhibit a distinct positive correlation betwee chloride and acidity in samples of pH < 5·7. The first-order correlation coefficients for hydrogen io and chloride in deposits from Sheffield, and from Manchester and Salford, are shown to be highly significan while those for hydrogen ions and sulphate are not significant. It is therefore suggested that hydrochlor acid should be considered in assessing the causes of rain acidity in urban areas.

1. INTRODUCTION

In the course of studies on the chemistry of rain (Gorham 1958) it was inferred from certai aberrant chloride/sodium ratios that hydrochloric acid might sometimes accompany sulphur acid in air pollution reaching the Lake District. It therefore seemed of interest to see whethe more direct evidence could be found for the presence of hydrochloric acid in rain, by examinin data collected from the centres of air pollution themselves.

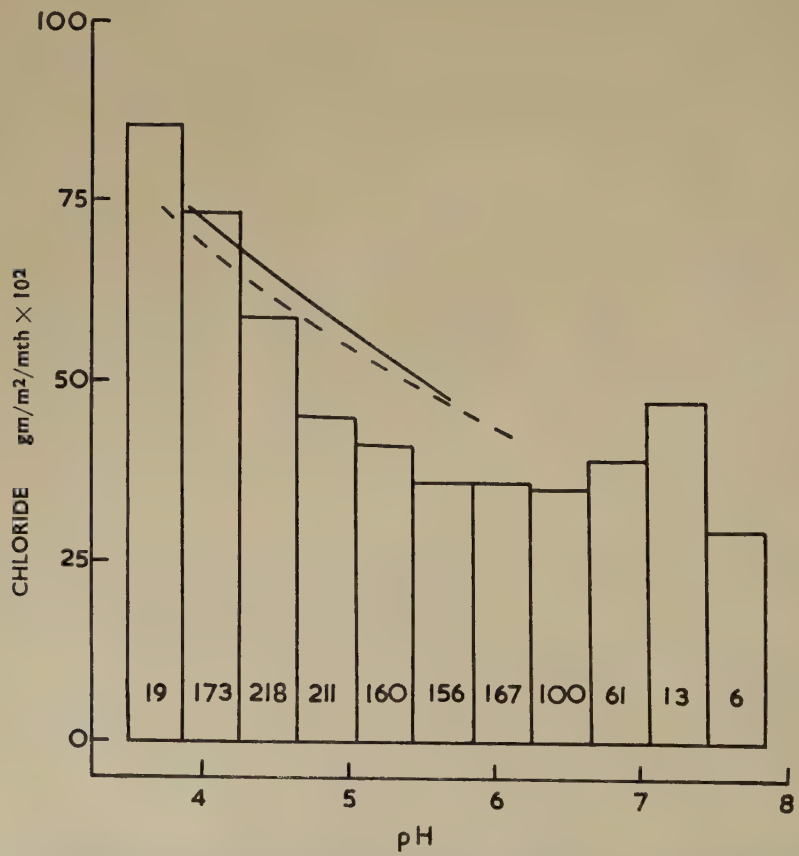

Figure 1. The relation between chloride deposit in British towns and cities and the pH of the precipitation. Rectangles (with numbers of samples inset) represent average chloride deposit for successive pH intervals, over the whole of Britain; while the curves represent the partial regressions for Sheffield (solid line) and for Manchester and Salford (dashed line).

2. Chloride and pH in atmospheric deposits from urban areas

Fig. 1 summarizes 642 series of summer and winter analyses for chloride and pH in British towns and cities, listed in Table 8 of the 27th report of the Department of Scientific and Industrial Research on the investigation of atmospheric pollution (1955). From this graph, in which the logarithmic averages of chloride deposit are plotted versus pH, it is evident that in those areas where acidity of precipitation exceeds that of distilled water in equilibrium with atmospheric carbon dioxide (pH *c.* 5·7), the deposits of chloride are greater than in areas where the rain is more nearly neutral. Moreover, with increasing acidities below pH 5·7, chloride deposits rise steadily, from 36 grams per 100 square metres per month to more than double this figure below pH 4·0. If chloride were plotted on a logarithmic scale versus pH, the relationship would be approximately linear below pH 5.

3. Zero- and first-order correlations of hydrogen ions with chloride and sulphate

While Fig. 1 suggests that hydrochloric acid may well be an important air pollutant in British cities, pH may also be strongly influenced by sulphuric acid, and it would seem desirable to test the partial correlations of hydrogen ions with both chloride and sulphate. For this purpose 27 series of both summer and winter analyses for pH, chloride and sulphate in atmospheric deposits at Sheffield were abstracted from the D.S.I.R. report mentioned previously, together with some 31 such series from Manchester and Salford. These cities were chosen because of the large number of different collecting stations, the marked acidity of the precipitation, and the inland situation relatively far from marine sources of chloride.

Since the amounts of ions brought down by rain tend toward logarithmic frequency distributions, a logarithmic transformation of the chloride and sulphate data was employed. In addition the pH values were converted to logarithms of the hydrogen ion deposit per unit area, using the rainfall figures given in the above report. Then the coefficients (r) were calculated for the correlation of hydrogen ions with chloride and sulphate, both before (zero-order) and after (first-order) elimination of the influence of the alternate anion, following the methods outlined by Brooks and Carruthers (1953). The values are given in Table 1.

TABLE 1. Coefficients for the correlation of hydrogen ions (Y) with chloride ions (X) and sulphate ions (Z) in atmospheric precipitation at Sheffield and in the Manchester-Salford area

	Chloride		Sulphate	
Sheffield $N = 54$	r_{YX}	0·62	r_{YZ}	0·40
	$r_{YX \cdot Z}$	0·51	$r_{YZ \cdot X}$	− 0·10
Manchester and Salford $N = 62$	r_{YX}	0·59	r_{YZ}	0·48
	$r_{YX \cdot Z}$	0·38	$r_{YZ \cdot X}$	0·03

It is apparent that while the zero-order coefficients are highly significant for both anions, the values for chloride are considerably greater than those for sulphate. Moreover, after partial correlation the coefficients for chloride remain highly significant, while those for sulphate are much reduced and become quite insignificant. Thus it would seem that in Sheffield, and in Manchester and Salford, hydrochloric acid is the agent mainly responsible for lowering the pH of precipitation, although the deposit of sulphate is roughly twice as heavy as that of chloride. (It is of course true that the deposit of hydrogen ions only amounts to a small percentage of that of either anion on an equivalent basis).

4. Discussion

The partial regression of hydrogen ion deposit (as mg/100 m^2/mth) upon that of chloride (as g/100 m^2/mth) is given for Sheffield by the equation $H = 0{\cdot}007\ Cl^{2{\cdot}36}$, and for Manchester and Salford by the equation $H = 0{\cdot}84\ Cl^{1{\cdot}44}$. According to these equations the proportion of chloride ions balanced by hydrogen ions increases (on an equivalent basis) as the chloride deposit becomes heavier. To see how these two areas compare with other towns and cities in

Britain the partial regressions of chloride on hydrogen ions have been re-calculated to pH values (assuming an average monthly rainfall of 54 mm in Sheffield and of 73 mm in Manchester and Salford) ; and the relationships are illustrated in Fig. 1 by two curves, the slopes of which show a general similarity to the trend exhibited over the whole of Britain. However, the relative predominance of hydrochloric and sulphuric acid over the whole range of British cities remains of course to be established. Since the main source of hydrochloric acid is likely to be coal combustion, one factor favouring its predominance in Sheffield and Manchester is the relatively high chlorine content of the coals used in these areas. Further statistical studies of individual monthly analyses from single deposit gauges might do much to elucidate the local aspects of the problem.

It also remains to determine why in fact hydrochloric acid should be responsible for the low pH values of precipitation in the Sheffield and Manchester areas, to the apparent exclusion of sulphuric acid in spite of the large sulphate deposits. This surprising phenomenon suggests that sulphur dioxide oxidizes rather slowly, and that only the portion which has both oxidized and reacted with basic substances is trapped in the deposit gauge. In this connexion it may be remarked that there is a strong correlation between sulphate and calcium in the deposits, the latter ion amounting on an equivalent basis to three-fifths of the total sulphate in Sheffield and about half in Manchester and Salford. Ammonia is also known to be correlated with sulphate in condensation nuclei produced by fuel combustion (Junge 1954), and in acid rains of pH less than 5·7 (Herman and Gorham 1957), so that it may well account for some of the residual sulphate in the deposit gauges. The difficulty with which gaseous sulphur dioxide is precipitated is also suggested by the calculations of Meetham (1950, 1954), who finds that only about one-seventh of that emitted is subsequently recorded as caught by the deposit-gauge technique, and estimates the average life of a sulphur-dioxide molecule in the atmosphere to be about 9 hours, by which time it may well have travelled far from its urban point of origin, possibly absorbed on smoke particles. In contrast, gaseous hydrogen chloride is probably much more readily captured and precipitated by water droplets, either in the chimneys or in the atmosphere ; for not only is it considerably more soluble than sulphur dioxide, but it also lowers the vapour pressure of water to a greater extent, so that the droplets may grow more rapidly to a size allowing their precipitation.

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Non-circular normal wind distributions

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(Manuscript received 21 February 1958)

SUMMARY

A series expansion for computing the distribution of wind speed for non-circular normal wind distributions is derived.

The form of the distribution is evaluated in a typical case.

1. INTRODUCTION

Approximate methods for the determination of the statistical distribution of wind speed when the vector random wind has a circular normal distribution have been discussed by Brooks, Durst and Carruthers (1946), by Brooks, Durst, Carruthers, Dewar and Sawyer (1950) and by Brooks and Carruthers (1953). Knighting (1954) has obtained the analytical form of the distribution in a form suitable for computation. Similar analytical expressions have been used for calculating tables of probabilities for offset circular targets in bombing problems (Groves and Smith 1957), to which the corresponding wind distribution problem is equivalent.

For targets of arbitrary shape, polar probability graph paper can be used. This is polar graph paper in which the areas of the cells are arranged so that each corresponds to the same known probability. The outline of the target is drawn on the paper on a scale determined by the standard deviation of hits, and the probability of a hit falling in the area is then obtained by counting the number of cells covered by the target. An alternative method described by Van Brocklin and Murray (1956) is to apply a graphical transformation which maps the boundary on to a plane in which equal probabilities are represented by equal areas so that ordinary graph paper can be used. This is useful because circular probability paper is not generally available in this country.

Either of these graphical methods can be applied to finding the distribution of wind speeds when the vector random wind has a non-circular normal distribution, but since a number of boundaries have to be drawn to cover the whole distribution they are laborious and subject to appreciable graphical error.

Scott (1956) has derived in closed form the distribution for the end point of the wind vector ending inside any of the similar ellipses constituting the contours of the non-circular wind distribution. It is more important, however, to be able to find the distribution of actual wind speed, i.e., to calculate the probability that the wind vector ends inside a circle of given radius whose centre is at the origin from which the wind vector is drawn.

2. THEORY

In this note it will be assumed that the components of the vector random wind along and perpendicular to the vector mean wind $\bar{v}$ are uncorrelated. If σ_x, σ_y denote the standard deviations of the wind components in these directions, the probability that a wind vector taken at random has its end point in an elementary region $dx\,dy$ at (x, y) is

$$\frac{1}{2\pi\,\sigma_x\,\sigma_y}\exp\left[-\tfrac{1}{2}\left\{\frac{(x-\bar{v})^2}{\sigma_x^2}+\frac{y^2}{\sigma_y^2}\right\}\right]dx\,dy$$

$$=\frac{1}{2\pi\,\sigma_x\,\sigma_y}\exp\left[-\frac{1}{2\,\sigma_x^2\,\sigma_y^2}\{\sigma_y^2\,(r\cos\theta-\bar{v})^2+\sigma_x^2\,r^2\sin^2\theta\}\right]r\,dr\,d\theta$$

on converting into polar co-ordinates (r, θ). This may be re-written as

$$\frac{1}{2\pi\,\sigma_x\,\sigma_y}\exp\left[-\frac{\bar{v}^2}{2\,(\sigma_x^2-\sigma_y^2)}-\frac{r^2}{2\,\sigma_y^2}+\frac{r^2\,(\sigma_x^2-\sigma_y^2)}{2\,\sigma_x^2\,\sigma_y^2}\left\{\cos\theta+\frac{\sigma_y^2\,\bar{v}}{r\,(\sigma_x^2-\sigma^2{}_y)}\right\}^2\right]r\,dr\,d\theta.$$

Integrating with respect to θ, we have to evaluate an integral of the form

$$I = \int_0^{2\pi} e^{b\,(2\cos\theta + \lambda)^2}\, d\theta$$

where

$$b = r^2\,(\sigma_x^2 - \sigma_y^2)/8\,\sigma_x^2\,\sigma_y^2, \quad \lambda = 2\,\sigma_y^2\,\bar{v}/r\,(\sigma_x^2 - \sigma_y^2)$$

which can be done by contour integration round the unit circle $z = e^{i\theta}$. The integrand is then $\exp\,(z + \frac{1}{z} + \lambda)^2/iz$, which has an isolated essential singularity at the origin. By the theory of residues the value of the integral is 2π times the constant term in the Laurent expansion of the numerator. Expanding the exponential in powers of $(z + z^{-1})$ and picking out the constant term we find

$$I = 2\pi \sum_{s=0}^{\infty} u^s \sum_{n=0}^{\infty} \frac{b^n\,\{2\,(n+s)\}\,!}{(n+s)\,!\,(n\,!)^2\,(2s)\,!}$$

where

$$u = \lambda^2\,b = \sigma_y^2\,\bar{v}^2/2\,\sigma_x^2\,(\sigma_x^2 - \sigma_y^2).$$

If therefore we put

$$\sigma_1 = \sigma_x\,(\sigma_x^2 - \sigma_y^2)^{\frac{1}{2}}/\sigma_y, \quad \sigma_2 = \sigma_x\,\sigma_y/(\sigma_x^2 - \sigma_y^2)^{\frac{1}{2}}$$

the frequency between radii r and $r + dr$ is

$$\frac{1}{\sigma_x\,\sigma_y} \exp\left\{-\frac{\bar{v}^2}{2\,(\sigma_x^2 - \sigma_y^2)} - \frac{r^2}{2\,\sigma_y^2}\right\} \sum_{s=0}^{\infty} \sum_{n=0}^{\infty} \frac{\{2\,(n+s)\}\,!}{2^{3n+s}\,(n+s)\,!\,(n\,!)^2\,(2s)\,!} \left(\frac{\bar{v}}{\sigma_1}\right)^{2s} \left(\frac{r}{\sigma_2}\right)^{2n} r\,dr.$$

The frequency for all directions for winds speeds between v and ∞ is therefore

$$F = \frac{\sigma_2^2}{2\,\sigma_x\,\sigma_y} \exp\left\{-\frac{\bar{v}^2}{2\,(\sigma_x^2 - \sigma_y^2)}\right\} \sum_{s=0}^{\infty} \sum_{n=0}^{\infty} \frac{\{2\,(n+s)\}\,!}{2^{3n+s}\,(n+s)\,!\,n\,!\,(2s)\,!} \left(\frac{\bar{v}}{\sigma_1}\right)^{2s} I_n$$

where

$$I_n = \frac{1}{n\,!} \int_{\left(\frac{v}{\sigma_2}\right)^2}^{\infty} e^{-aw}\, w^n\, dw \quad \text{and} \quad a = \tfrac{1}{2}\left(\frac{\sigma_2}{\sigma_y}\right)^2.$$

I_n may be readily integrated by parts, but as it yields the cumulative Poisson distribution it has been widely tabulated. A useful set of tables is that given in Biometrika Tables, Vol. 1 (Pearson and Hartley 1954). The function there tabulated is designated

$$Q\,(\chi^2|\nu) = 2^{-\frac{1}{2}\nu}\,\{\Gamma\,(\tfrac{1}{2}\,\nu)\}^{-1} \int_{\chi^2}^{\infty} e^{-\frac{1}{2}x}\, x^{\frac{1}{2}\nu - 1}\, dx$$

which is equal to $e^{-m} \sum_{j=0}^{c-1} m^j/j\,!$ when ν is even and $m = \frac{1}{2}\,\chi^2$, $c = \frac{1}{2}\,\nu$.

Applying this to the above expression for F, we have

$$F = \frac{\sigma_y}{\sigma_x}\, e^{-\frac{\bar{v}^2}{2\,(\sigma_x^2 - \sigma_y^2)}} \sum_{s=0}^{\infty} \sum_{n=0}^{\infty} \frac{\{2\,(n+s)\}\,!}{2^{2n+s}\,(n+s)\,!\,n\,!\,(2s)\,!} \left(\frac{\sigma_y}{\sigma_2}\right)^{2n} \left(\frac{\bar{v}}{\sigma_1}\right)^{2s} Q\left(\frac{v^2}{\sigma_y^2}\middle|\, 2n+2\right).$$

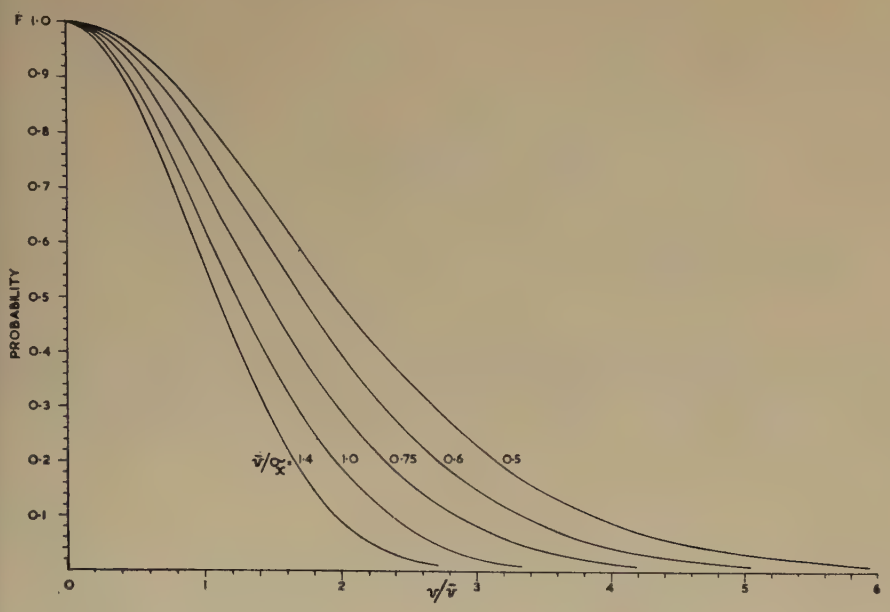
This series expansion is fairly rapidly convergent when representative values of the parameters are inserted.

3. Application of series expansion

The series for F was evaluated for the case $\sigma_y : \sigma_x = 1 : \sqrt{3}$, which on expressing all quantities in terms of σ_x becomes

$$F = \sqrt{3}\, e^{-\frac{1}{2}(\bar{v}/\sigma_x)^2} \sum_{s=0}^{\infty} \sum_{n=0}^{\infty} \frac{\{2\,(n+s)\}\,!}{3^{n+1}\,2^{n+2s}\,n\,!\,(n+s)\,!\,(2s)\,!} \left(\frac{\bar{v}}{\sigma_x}\right)^{2s} Q\left(\frac{3v^2}{\sigma_x^2}\middle|\, 2n+2\right).$$

The results are plotted in Fig. 1 as curves of F against $v/\bar{v}$ for different values of $\bar{v}/\sigma_x$.



gure 1. Wind speed distribution in case $\sigma_y : \sigma_x = 1 : \sqrt{3}$. Probability of wind speed exceeding assigned values for different values of v/σ_x.

4. Conclusions

The above series expansion provides a means of deriving the distribution of wind speeds itable for numerical computation for winds having a non-circular normal distribution in the se where the wind vector is symmetrically distributed about the vector mean wind.

The more general case of a non-symmetrical distribution about the vector mean wind could doubt be treated analytically, but the expressions would be much more complicated.

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Dust concentrations in the Harmattan

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(Manuscript received 14 January 1957; in revised form 13 January 1958)

SUMMARY

A method of counting the very fine dust particles of the Harmattan and of determining their approxima size range is described, and some of the counts obtained at Ibadan, Nigeria, during the 1955-56 season a presented. It is suggested that the large dust concentrations may have a blanketing effect on terrestr radiation.

1. INTRODUCTION

Hamilton and Archbold (1945) described fully the dust storms of the southern Sahara ar the resultant dust haze often encountered in northern and central Nigeria, though infrequent in the south. They enumerated the constituents of the coarser dust and mentioned ' a quanti of very fine dust, indeterminate microscopically.' This very fine dust may originate in th Faya Largeau area of the Sahara, or it may be picked up by the wind in the dry savanna country of central Nigeria. As the bright sunshine totals for cloudless days at Kano often excee corresponding totals for the southern regions during an extensive Harmattan, the latter proce may well predominate.

The abrasive and penetrating properties of the very fine dust suggest that it is made up tiny quartz particles. The slow process of erosion in the desert, principally by the effect describe as ' saltation ' by Bagnold (1941), would be similar to a slow inexorable grinding, producing ver small particles of varying shape, certainly not spherical, and having specific gravities of about 2·

2. COUNTING TECHNIQUE

Very small particles of irregular shape settle under gravity with a velocity v given by Martin (1926-27) formula

$$v = 36\left(\frac{\rho - \rho_0}{\eta}\right) d^2 \qquad . \quad . \quad . \quad . \quad . \quad (1$$

where ρ, ρ_0 are the relative densities of the particles and of the fluid respectively, d is the particl diameter, and η the coefficient of viscosity. Multiplying this by Cunningham's (1910) correctio term $(1 + 1{\cdot}7\ \lambda/d)$ where λ is the mean free path of the surrounding air molecules; neglecting ρ in comparison with ρ; assuming an average temperature of 27°C and pressure 74·5 cm, we ge for quartz particles settling in air

$$v = 4{\cdot}9 \times 10^5\,(d^2 + 1{\cdot}1 \times 10^{-5}\,d) \qquad . \quad . \quad . \quad (2$$

The settling times in a Casella Settlement Counter with a specially enlarged cylinder of heigh 17·4 cm are as follows:

d (μ)	Time
1·0	53 min
0·5	3 hr 15 min
0·4	4 hr 50 min
0·3	8 hr
0·2	15 hr 55 min
0·1	47 hr
0·08	65 hr
0·06	97 hr

Particles smaller than 0·06 μ in diameter would be subject to Brownian movement with a ver slow downwards diffusion.

Samples of the dust-laden air were normally taken at 1600 LMT, when the surface layers of he atmosphere were well mixed by turbulence, on afternoons when the relative humidity was 0 per cent or lower. The instrument site was well away from busy laterite roads, with uncut ush stretching for many miles to the north. Size grading was attempted, using the five available over glasses of the Casella Counter, as often as possible. With the above settling times, this ften meant only once every four days. On the other days total counts only were taken, using ylinders of identical dimensions but with bases of simpler construction.

The cover glasses were examined with a Beck (Model 47) microscope, using 16 mm and 4 mm bjectives and an × 10 eyepiece. Dark-ground illumination was supplied through a Fresnel homb. A graticule of 1 mm squares was used in counting the numbers of the smaller particles vhich showed up as little specks of light, or as tiny diffraction centres.

No permanent records of the dust samples could be kept. Fungi grow rapidly on any glass urface in Nigerian conditions, and the fixative liquids normally used in work of this sort were lways found to have large concentrations of sub-microscopic detritus in them, whether of Harmattan origin or not, being hard to say.

This simple settlement technique has definite advantages in Harmattan conditions over mpactor-type instruments. The author considers that it could only be bettered by the use of a hermal precipitator and an electron microscope – instruments which are many times more xpensive.

3. Sizes and concentrations

Of the eight size gradings attempted, six showed about 80 per cent of the particles in the ·2-0·3 μ diameter range. The other two gave about 75 per cent of the particles in the 0·3-0·4 μ ange.

The observations of humidity mixing ratio, visibility, and dust concentration are shown n Table 1 for certain selected dates.

TABLE 1. Observations at 1600 LMT of humidity mixing ratio, visibility and dust concentration

Date	h.m.r. (g/kg)	Vis. (mi)	D. conc. (10^3/cm^3)
26.12.55	8·8	4	300
27.12.55	5·3	10	92
28.12.55	10·6	5	190
29.12.55	7·8	7	180
30.12.55	7·0	5	370
31.12.55	8·1	7	150
16.1.56	12·7	2	480
17.1.56	10·8	2	370
20.1.56	13·5	5	110
21.1.56	14·0	7	110
22.1.56	11·7	7	110
29.1.56	15·1	10	57
30.1.56	13·7	7	120
31.1.56	12·7	7	130
1.2.56	14·2	7	140
2.2.56	13·2	7	60

During the rainy season the visibility seldom exceeds 25-30 mi and there is virtually no dust (of the size here investigated). The humidity mixing ratio is approximately 20 g/kg.

Concentrations of the larger dust particles, having diameters exceeding one micron, are normally very small. There are records of falls of dust particles on the decks of ships far out in the Atlantic off the coast of West Africa. At Ibadan, there is a definite fall-out of large dust particles at about 2300 LMT. This is quite visible to the naked eye on the slides of a Hirst Spore Counter operated at Moor Plantation. It is possible that the fall of these larger dust particles from the higher layers is accelerated by their having a condensation coat which could only form when the relative humidity reached about 90 per cent in the evening. The fall of one of these large particles is, however, a rare event in an instrument such as the Casella Chamber. In persistent Harmattan conditions the small dust particles are about ten thousand times more plentiful than the large, and so are likely to play a correspondingly more important part in the radiation budget of the atmosphere and in the incidence of low visibilities.

4. Nocturnal cooling rates

In the severe Harmattan of the last five days of December 1955 it was observed that the average rate of cooling, measured in a screen, was 1·5°F/hr between 2000 LMT and midnight, but between midnight and sunrise the average rate was 1·7°F/hr. Bearing in mind the copious dew formation in these weather conditions before sunrise – which would normally retard the surface cooling – it would appear that either cooler air is flowing in from the north, or that a large fall-out of dust at midnight is permitting a greater rate of escape of terrestrial radiation. The inference that fine dust particles may affect terrestrial radiation is in agreement with Veryard (1936), but directly contradicts one statement made by Hamilton and Archbold.

Two exceptional thermograph traces support the view that large concentrations of dust have a shielding effect on the earth at night.

(a) The lowest night minimum temperature of the 1955-56 season, 48°F, a record for this part of Nigeria, occurred during a period of persistent Harmattan on 28 December 1955, when the dust concentration the previous afternoon had fallen to its lowest value for that whole week. Visibility was also at its highest.

(b) A big fall-out of dust probably took place on the night of 14 January 1956. The average cooling rates before and after midnight were 0·8°F/hr and 2·3°F/hr respectively. The minimum temperature was recorded on the thermograph trace at 0330 LMT, after which the south-westerly air stream must have broken down the inversion, as the temperature rose gradually. An air sample taken at 2300 LMT showed 150,000 dust particles/cm^3, whereas one taken the following day at 1600 LMT yielded the negligibly small count of 2,000/cm^3.

Acknowledgments

The author's thanks are due to the Director of the Nigerian Meteorological Services for the assistance he so often gave; also to Professor B. J. Garnier of University College, Ibadan, and to Mr. J. E. Pretty of the Nigerian College of Technology for their co-operation, data, and advice.

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Correspondence

551.578.42 (42)

Snowfall frequency in metropolitan England

By L. C. W. Bonacina

Professor Manley's very interesting figures in the January issue (p. 70) show one or two utstanding anomalies which I would like to ask him to clarify. The reduction of the figures rtually to sea-level, eliminating the altitude factor, leaves them to show up two other influences fecting snowfall : (1) local topographical factors independent of altitude and (2) wider regional ctors.

As to (1), Professor Manley has cited the Chiltern scarp in relation to Whipsnade, but, of ourse, in an area of generally low and simple relief like SE England, topographical factors have one of the complexity of mountainous country where, for example, the frequency of snowflakes aching the bottom of a deep valley might well be increased by the presence of much snow lying n the encompassing mountain ridges.

As to (2), Professor Manley's ' metropolitan England ' is certainly amply wide enough in its nge from East Anglia to the Cotswolds to include regional differences in the liability to snowfall. et while Mildenhall in Suffolk shows the suggestively high reduced figure of 19·5 days, Wye ith only 10·9 days does not reflect the slightest indication of its position in the downland of the ther notoriously snowy district of East Kent. In fact the figure for Wye in the B category is arely two-thirds that of Hampstead, 16·5 days, in the A category. Professor Manley has referred Hampstead's ' very high standard ' of watchfulness and, indeed, I have my own reasons for elieving this station to be particularly vigilant for flakes of snow.

But I have long been of opinion that the comparability of snow-frequency statistics is affected ot only by differences in alertness but also by the real difficulties presented by such border-line ases as cold sleety rain on the one hand, and the several varieties of soft hail on the other, some f which are akin to snow.

3 Christchurch Hill,
Hampstead, London, N.W.3.
1 February 1958.

Reply

By Gordon Manley

I have to thank Mr. Bonacina for his comments; I am glad that my intention to bring out the actors he names has been appreciated. Among stations beyond the Thames Basin I chose Mildenhall and South Farnborough to bring out the slow ' regional ' decline southwestward. have not gone into the question of the constancy of the watch kept at Dunstable or Whipsnade, ut I certainly think that northerly showers in unstable Arctic air are likely to be touched off y that escarpment, to judge by what happens elsewhere.

Wye, lying as it does in the gap 9 mi SW of Canterbury, is also partly sheltered to leeward of he Downs; and I see no reason why its average should differ from that at East Malling. The umber of days on which an air mass capable of allowing snowflakes to descend to ground level eaches East Kent cannot differ significantly from that at London. That there is a tendency for nore frequent snow-cover on the uplands arises from the fact that more snow is liable to fall n those days. Orography plays its part and now and then there is some drifting. Instability howers are heavier and more frequent, and on some days will fall on the hills while the lowlands leeward remain free.

Having at hand the *Annual Weather Report* since 1924, I have taken out the data for all the vailable East Kent stations. Dover provides the only complete record; Lympne gives 28 years, Manston 17 years. For purposes of comparison with Wye and other stations elsewhere, I have educed the results of all the observations to the averages which would be likely to apply to the 0-year period, 1926-55. I have left out of account the very short records at Deal, Herne Bay, Elmstone and Rye; that at Deal in particular certainly cannot be ranked with such a station as Dover.

Among the ' first-class ' records we have : Lympne (346 ft) 19·2 and Manston (154 f 17·0. For comparison, Croydon (217 ft) gives 18·6.

The useful ' coastal ' stations, north and south, are : Whitstable 11·8, Margate 10·5, Ramsga 10·0, Dover 13·2, Folkestone 14·0, Dungeness 10·0. Of these last, Dover and Folkestone appea to be ' good B ' ; the others grade downwards and broadly compare with Wye.

Inland, Canterbury provides no snow data, and Lympne lies south of the Downs. Apart fro Goudhurst (20 mi west of Wye) which at 290 ft gives an average of only 11·0 and need not be di cussed, there are only two very short records from the upland towards the North Downs. Sitting bourne (224 ft) has 6 years' observations which support a 30-year average of about 14. Throwle (493 ft) has 4 years' observations which hint at an average of the order of 23. This makes ver scanty evidence, but it leads me to think that on the Downs in East Kent a first-class station at sa 500 ft could well give an average of the order of 28, that is about four more than the average Biggin Hill. In respect of the additional incidence of instability showers this would not be ou of keeping with the findings at Whipsnade.

I cordially agree with what Mr. Bonacina says about rainy sleet and soft hail; this is why think we must begin to place our trust in the ' first-class ' airfields. ' Soft hail ' becomes a besettin problem in the reduction of the records kept by some of the more enthusiastic Victorians; one ha to go to the temperature records kept on the day in question to try to elucidate some of the reports of ' snow ' in summer months. I have long felt it desirable to bring some rational orde into our observations of snowfall; we are still beset by absurdly exaggerated accounts from orga nizations which ought to know better.

Bedford College,
University of London,
Regent's Park, N.W.1.
17 March 1958.

551.558.22

Airflow over mountains : indeterminacy of solution

By G. A. Corby and J. S. Sawyer

In his contribution to the correspondence columns of the April issue, Scorer (p. 182 discusses the solution of the equation obtained by perturbation methods for ζ, the vertical displace ment of a particle at (x, z) in the air flowing over a two-dimensional mountain ridge, viz.

$$\frac{\partial^2 \zeta}{\partial z^2} + (l^2 - k^2)\,\zeta = 0 \qquad (1$$

For l independent of z, he writes the solution as

$$\zeta = A \cos \mu z + B \sin \mu z \qquad (2$$

where $\mu = + (l^2 - k^2)^{\frac{1}{2}}$

As A and B must be harmonic in the x direction with wavelength $2\pi/k$ we can write this as

$$\zeta = (C \cos kx + D \sin kx) \cos \mu z + (E \cos kx + F \sin kx) \sin \mu z \qquad (3$$

where, so far, C, D, E and F are arbitrary functions of k.

For a Fourier component $\cos kx$ at the ground ($z = 0$), the solution Eq. (3) becomes

$$\zeta = \cos kx \cos \mu z + (E \cos kx + F \sin kx) \sin \mu z \qquad (4$$

So far there can be no dispute. The difference of opinion arises when we come to assign values to E and F. Part of Scorer's latest argument amounts to saying ' as we have no clear-cut second boundary condition to tell us the proper values of E and F, let us exclude all solutions which we are not obliged to include to satisfy the ground boundary condition, i.e., let us put $E = F = 0$.' This appears a rather arbitrary line for a mathematician to take. Surely we should seek an additional physical argument or constraint which makes the solution unique and in the treatments of all other authors (including Scorer himself in the past) specific methods have been sought for deciding on the values of E and F.

If, for convenience, we examine the complex solution of Eq. (1), we find that the most neral solution is

$$\zeta = (Ge^{i\mu z} + He^{-i\mu z})\, e^{ikx} \quad . \quad . \quad . \quad . \quad (5)$$

here G and H are complex arbitrary functions of k. As Eq. (1) contains no complex coefficients e real and imaginary parts of the expression (5) are themselves solutions of Eq. (1).

Writing G and H in terms of their real and imaginary parts, we have

$$\zeta = \{(G_1 + iG_2)\, e^{i\mu z} + (H_1 + iH_2)\, e^{-i\mu z}\}\, e^{ikx} \quad . \quad . \quad . \quad . \quad (6)$$

$$\begin{aligned} &= [\{(G_1 + H_1)\cos kx - (G_2 + H_2)\sin kx\}\cos \mu z \\ &\qquad - \{(G_2 - H_2)\cos kx + (G_1 - H_1)\sin kx\}\sin \mu z] \\ &+ i\,[\{(G_2 + H_2)\cos kx + (G_1 + H_1)\sin kx\}\cos \mu z \\ &\qquad + \{(G_1 - H_1)\cos kx - (G_2 - H_2)\sin kx\}\sin \mu z] \quad . \quad . \quad (7) \end{aligned}$$

It will be noted that both the real and imaginary parts of Eq. (7) have the same form as q. (3). If we now put $\zeta = e^{ikx}$ at $z = 0$ we obtain $G + H = 1$, or $G_1 + H_1 = 1$, $G_2 + H_2 = 0$.

The real part of Eqs. (6) or (7) then represents the flow over the ground contour $\zeta_0 = \cos kx$ nd the imaginary part the flow over $\zeta_0 = \sin kx$. The real part is precisely equivalent to Eq. (4).

If now, as a result of quite separate reasoning about the second boundary condition, we ecide that $H = 0$ in Eq. (5) then we quite properly write the solution for the flow over the ountain $\zeta_0 = \int_0^\infty \cos kx\, f(k)\, dk$ as

$$\zeta = \text{real part of } \int_0^\infty e^{i\mu z}\, e^{ikx}\, f(k)\, dk$$

he imaginary part is of course the flow over $\zeta_0 = \int_0^\infty \sin kx\, f(k)\, dk$. The form of solution elected has nothing to do with errors in the use of complex notation – it is quite deliberate. Ve are not under the mistaken impression that (real part of $e^{i\mu z}\, e^{ikx}$) = (real part of $e^{i\mu z}$) eal part of e^{ikx}).

If we avoided complex notation altogether and proceeded from Eq. (4) the same upper- oundary reasoning would lead to the equivalent decision $E = 0$, $F = -1$. The retention f a term in $\sin kx$ could clearly not then be due to including inadvertently part of the solution ppropriate to the ' imaginary ' mountain. The lee-wave term contains the factor $-\sin kx$ vhich is picked out from e^{ikx} because of the presence of an additional factor ' i.' Would Dr. corer maintain that this too is really appropriate to the ' imaginary ' mountain ?

Another point which has a bearing may be mentioned here. As we are only considering he case with l independent of z, there appears no reason why, if we ' freeze ' a streamline and egard it as a new mountain the flow above should change. Either of the solutions $e^{i\mu z}$ or $e^{-i\mu z}$ is atisfactory in this respect but if we adopt any mixture of them, then regarding an upper streamline s a new mountain yields a different flow above. In terms of Eq. (4) this means that only $= 0$, $F = \pm 1$ provide solutions which satisfy this test. This argument cannot be demolished y citing the case of flow containing nodal surfaces because such surfaces can never occur. This s because the vertical wave length $2\pi/\mu$ varies with k and no plane *within the fluid* could be a odal surface for all the Fourier components; this is true whatever secondary boundary condition s adopted – even if this is a rigid upper boundary.

Thus, in spite of Scorer's argument, it appears that the only choice open to us is between $= 0$ or $H = 0$ in Eq. (5). In some techniques for making this choice the final result is really letermined by deciding on which side of the mountain ridge, windward or lee, it is appropriate or infinite trains of waves to occur. If these are not acceptable on the windward side we are bliged to take $H = 0$. If, on the other hand, we predetermined the second boundary condition n the manner Scorer now proposes and then applied these techniques we should reach the mbarrassing conclusion that ' lee ' waves occur with equal amplitude on both sides of the nountain ! In other words, it would be quite inconsistent to insert lee waves on the downstream ide only whilst at the same time using the second boundary condition now put forward by Scorer.

Meteorological Office,
Air Ministry, Dunstable,
Bedfordshire.
4 May 1958.

551.594

William Bulkeley's auroral observations

By Cicely M. Botley

With regard to Mr. Oliver's interesting discussion of auroral observations in the Apr issue (p. 126), the conclusions reached by D. J. Schove (*J. Geophys. Res.*, **60**, p. 128, 1955) as t solar activity during the period provide an interesting commentary. Bulkeley's first period 1734-4 falls before the time of generally available ' sunspot numbers ' as calculated by Wolf, but Schove's estimate for the maximum of 1738·7 is 110 ' strong ' and the character of the 30-year aurora period ending 1746, ' very strong ', including the amazing but apparently authentic observatio of aurora at Cuzco, Peru, 20 August 1744, within a few degrees of the geomagnetic equator (H. Fritz, *Catalogue of observations of aurorae*, Vienna, 1873).

Bulkeley's second period 1747-1760 comprises a period of decline clearly shown on the curv in Fig. 1 in Schove's paper. The maximum of 1750·3 is 80 ' medium ' and the Wolf numbers fo the succeeding years fall off sharply to 9·6 in 1755.

There also seems to have been a decline in the number of aurorae observed in Rome at thi time; perhaps some reader who has access to the data will confirm this.

2 Park Road,
Tunbridge Wells,
Kent.
6 May 1958.

551.509.311

An essay on low-latitude wind analysis

By C. E. Palmer

As there is some risk that readers of Mr. J. R. Scott's essay in the previous issue (p. 166) will attribute to me the incorrect and dogmatic ' assertion that . . . . a cloud line must alway coincide with a streamline,' I should like to repeat, to the point of tedium, the context of the discussion in the *Compendium of Meteorology*, to which he refers.

The entity under investigation in my text was the organized line of cumulonimbus found in the oceanic Pacific, which, *when it was accompanied by appropriate wind shifts in space and time on a synoptic scale*, had previously been identified as a front, i.e., an atmospheric discontinuity. The assertion was made that no consistent air-mass contrast could be found between the air on either side of such a line. The wind shift across the line was said to be gradual, not abrupt, and it was maintained that isogon analysis reveals that the line itself is coincident with what V. Bjerknes called a ' singular line ' but which I have named an ' asymptote ' (since the term singular, implies zero wind along the line).

No analyst with tropical experience, and in his right mind, would claim that all cloud lines must be streamlines. Cloud lines on all scales are very common, in the Trades for example, and hundreds of them have been photographed and studied over the tropical ocean; any preconceived orientation of these lines with respect to the gross wind field can be discovered by a conscientious synoptician. The tropical front, however, as it was once drawn in the Pacific on surface synoptic pressure maps, will appear on wind maps as an asymptote in the field of motion.

In addition to the misrepresentation, the paragraph of Mr. Scott's essay to which I take exception (p. 169) contains two errors. First, he indicates that the isogon analysis is comparatively objective but that subjectivity enters when the line elements (whose totality constitute the streamlines) are drawn. The only subjective part of the analysis lies in drafting the isogons. The ruling of the line elements is mechanical: a machine for ruling them has been described by V. Bjerknes (*Dynamic Meteorology and Hydrography*, Carnegie Institution, Washington, 1911, Pt. II, p. 67) and our group has used a mechanical ruling method, based on a different principle, for the past eight years on Pacific maps.

The second error arises from a rather common confusion of the streamline with the trajectory f an air parcel. Mr Scott states implicitly that an asymptote cannot move parallel to itself. deally the streamline pattern is an instantaneous one – it shows the field of motion at a given nstant, and being a purely kinematical picture, reveals nothing about its own time-dependence. Only through successive pictures, if one is treating it empirically, or through dynamics, if one is reating it theoretically, can one discover the velocity and changes in intensity of any topological eature of the wind field.

nstitute of Geophysics,
Jniversity of California,
Los Angeles 24, California.
6 May 1958.

551.594.2

Intracloud lightning discharges

By L. G. SMITH

(Read 15 January 1958. Presented by Dr. E. T. Pierce. See *Q.J.*, **83**, p. 103)

Mr. R. F. Jones : It is not true that many intracloud lightning discharges are greatly inclined to the vertical, even horizontal ? The simple bipolar model of positive charge at about 7·5 km vertically above a negative charge at about 2·5 km has always seemed unrealistic to me, having regard to the structure of the cumulonimbus as revealed by aircraft flights and radar. Would it be possible to explain the ground observations with other distributions of charge in the cloud, e.g., a sharply defined column of negative charge, extending perhaps as high as 13 km or so, surrounded in the higher levels by a volume of positive charge, the boundaries of which were less sharply defined ? I am thinking, of course, of negatively charged precipitation elements with positively charged ice particles in the anvil of the cloud.

Dr. J. A. Chalmers : It might be thought that an inclined discharge in a cloud could give a complex field change with two turning points, since the distance of the moving charge from the observer could decrease and then increase again, thus perhaps crossing the reversal distance twice. However, if one calculates the field change, it turns out that an inclined discharge cannot give more than one turning point, and therefore the more complex field changes require more complex movements of charge.

Dr. E. T. Pierce (*in reply, on behalf of the author*) : In reply to Mr. R. F. Jones it is certainly true that many intracloud lightning flashes are inclined, and that this is a complicating feature in the interpretation of field-change observations. There is, however, strong experimental evidence (e.g. Gish and Wait, *J. Geophys. Res.*, **55**, p. 473, 1950) that the simple vertical dipole is a good representation of the electrical state for some 50 per cent of all thunderclouds; for the remainder the electrical structure is too complicated to be accounted for by any simple distribution of charge. Thus, if any convenient model at all is to be adopted, and intolerable complexity thereby avoided, the vertical dipole would seem to be the one to use. Indeed, the considerable success of interpretation on this picture is in itself evidence for its validity.

The calculation described by Dr. Chalmers is interesting and confirms the conclusion of Dr. Smith that the more complex field-changes require complicated movements of charge for their explanation.

Dr. L. G. Smith (*in reply, communicated*) : I would like to thank Dr. Pierce for presenting my paper. Mr. Jones is justifiably critical of the use of a simple model to represent the charge distribution of a thundercloud. Similarly it is not to be implied from the analysis of slow field changes that the cloud discharge is necessarily as simple as the movement of one charged volume towards the other. Presumably the actual mechanism following the initiation of the discharge involved an upward developing leader analogous to, and perhaps identical with, the junction leader of a discharge to ground.

The inclination of the cloud discharge is one of the factors contributing to the wide range of the amplitudes of field changes shown in Fig. 5. However, although cloud discharges may not uncommonly have inclinations as great as 45 degrees to the vertical, I feel that more nearly horizontal cloud discharges are rare. The best evidence for this is Dr. Pierce's conclusion (*Q.J.* **81**, p. 211) that the reversal distance is never greater than 20 km. For the dipole inclined at 45 degrees which is discussed on p. 109, the maximum reversal distance, measured from the centre of the dipole, is 16·3 km.

Air discharges, which are often observed to be horizontal, are excluded from this investigation. It was established early in the course of the observations that air discharges produce a field change having a rapid component; the recording system was not of sufficiently rapid response to distinguish them from a discharge to ground having a single stroke.

Report of the Council

for the year 1957

Submitted to the Annual General Meeting, 23 April 1958

General

The Council are glad to report another year of satisfactory progress. A wide range of tivities has been undertaken and for the seventh year in succession the total membership as shown a small increase over the previous year.

The continued rise in costs and the loss in income from two important sources as explained the finance section caused a further deterioration in the Society's finances. Council, after ery serious consideration, decided the only way of putting the Society's finances on a satis-ctory footing would be by increasing membership fees and the *Quarterly Journal* subscription ith effect from 1 January 1958. The necessary amendment to the By-Laws was agreed at a pecial General Meeting held on 20 November. The financial benefit of these increases is, f course, not reflected in the accounts presented.

The fourth two-day Summer Meeting was held at Glasgow. Details are given later in the eport.

Three vacation courses were successfully held in conjunction with the Field Studies Council, he, mainly for members of Flying and Gliding Clubs, at the new Field Centre at Preston Montford and the others for undergraduates and sixth-form pupils respectively at the Malham Tarn and Flatford Mill Field Centres. Fourteen students were subsequently elected to member-hip of the Society.

Council

From 1 January to 30 September the constitution of the Council was as recorded in the 956 Annual Report.

From 1 October 1957 the following Council held office :

President

Professor Percival Albert Sheppard, B.Sc., F.Inst.P.

Vice-Presidents

Alan W. Brewer, Ph.D.
Charles Henry Brian Priestley, M.A., Sc.D., F.Inst.P.
Reginald Cockcroft Sutcliffe, O.B.E., Ph.D., F.R.S.
Richard George Veryard, B.Sc.

Vice-President for Canada

Robert Campbell Graham

Vice-President for Scotland

James Robert Atkinson, M.A.

Treasurer

James Strachan Farquharson, M.A., D.Sc.

Secretaries

Patrick John Meade, O.B.E., B.Sc.
Howard Latimer Penman, M.Sc., Ph.D., F.Inst.P.
George David Robinson, Ph.D., F.Inst.P. (Editor)
Arthur George Forsdyke, Ph.D., A.R.C.S. (Librarian)

Councillors

Ian Campbell Browne, M.A., Ph.D. (deceased 8 December 1957)
Instr. Capt. Charles Roy Darlington, B.Sc., R.N.
Thomas Vivian Davies, M.Sc.
Thomas Herbert Ellison, M.A., Ph.D.
Ronald Westlake Gloyne, B.Sc.
Frank Henry Winn Green, M.Sc.
Robert Frederick Jones, B.A.
Basil John Mason, D.Sc.
Robert James Murgatroyd, B.Sc.
Brian Cecil Vernon Oddie, B.Sc.
John Stanley Sawyer, M.A.
Charles Edward Wallington, M.Sc.

The Council met nine times during the year and there were thirty-four Committee Meetings

Meetings

Eight Ordinary Meetings and two Special General Meetings were held in the Society's rooms during the year, including a Discussion Meeting on ' New methods in the ozone problem ' and a joint Meeting with the National Institute of Oceanography on ' Long waves and storm surges.' A Special joint Meeting was held with the Royal Statistical Society on ' Analysis of geophysical time series ' at the London School of Hygiene and Tropical Medicine and a two-day international symposium with the Royal Astronomical Society on ' Planetary atmospheres and convection in rotating fluids ' at Burlington House.

Mr. H. H. Lamb gave the Popular Lecture on ' Weather in the polar regions ' twice in November. The Society's series of Popular Lectures was again extended to the Scottish and Manchester Centres.

The Annual General Meeting was held in the Society's rooms on 17 April when the Report of the Council and the Annual Accounts for 1956 were adopted. The Presidential Address was given by Dr. R. C. Sutcliffe, O.B.E., F.R.S., his subject being ' An outlook on meteorology and the Society.'

The Symons Memorial Lecture was given on 3 April by Professor C. F. Powell, F.R.S., Melville Wills Professor of Physics, University of Bristol, on ' Experiments at high altitudes with free balloons.'

The Summer visit on 13 July was to the Atomic Energy Research Establishment, Harwell, by kind invitation of Sir John Cockcroft, O.M., F.R.S. Owing to the heavy demand, a ballot was held to fill the available places. Council wish to express to Sir John Cockcroft and his colleagues their appreciation of a most interesting visit.

Two-day Summer Meeting, Glasgow, 3-5 July 1957

The fourth two-day Summer Meeting was held in the Department of Natural Philosophy, University of Glasgow, by kind permission of the University Court.

The meeting consisted of two scientific symposia with an attendance at each of about 70 members and guests. The first symposium consisted of papers on 'Cloud physics,' and amongst those present was Professor C. T. R. Wilson, F.R.S., Honorary Member.

The second symposium surveyed ' Problems of hill climate.'

By kind invitation of Professor P. I. Dee, F.R.S., there was a tour of the Department of Natural Philosophy when the staff and research students explained the equipment and techniques.

Two most enjoyable excursions were arranged to O.W.S. *Weather Watcher* at Greenock and to the hydro-electric scheme at Loch Sloy. Thanks are offered to the Director-General, Meteorological Office, and to the British Electricity Authority for the opportunities to make these visits.

The Council wish to record their sincere gratitude to Mr. J. R. Atkinson and his colleagues on the Scottish Centre Committee who were responsible for the excellent local arrangements.

Publications

The inflow of scientific communications for the *Quarterly Journal* was somewhat greater han in 1956 although it continued to be rather less than in previous years. Sixty-four papers ere submitted for publication during 1957 as against fifty-seven in 1956 and fifty papers were ublished during the year. The average time between receipt of approved copy and publication n the *Journal* was about 4½ months. The four numbers of the 1957 *Journal* together contained 72 pages as compared with 559 pages in 1956.

Council are greatly indebted to the Editor, Dr. G. D. Robinson, the Editing Committee nd the proof reader, Mr. E. L. Hawke, for their services in the production of the *Journal*.

The Society's monthly magazine *Weather* continued to maintain a high standard of pro- luction. Council are greatly indebted to the Weather Editing Committee for their valuable work.

A new venture was embarked on by the publication, under the auspices of the Society, f *Cloud study : a pictorial guide* by F. H. Ludlam and R. S. Scorer. This book, consisting of ntroductory and explanatory text and 75 photographs, many of which were supplied from the ociety's Clarke and Cave collections, has been well received. The publishers (John Murray) lready have a second edition in hand.

Membership

Table A

	Fellows and Foreign Members			Associates	Students	Honorary Members	Total
	Annual	Life	Total				
31 Dec. 1956	1,475	178	1,653	306	101	16	2,076
Since elected	102	—	102	—	30	—	132
Re-admitted	4	—	4	—	—	—	4
Transferred	13	3	16	− 1	− 15	—	—
Deceased	− 8	− 3	− 11	− 1	—	− 4	− 16
Resigned	− 58	—	− 58	—	− 6	—	− 64
Lapsed	− 27	—	− 27	− 3	− 3	—	− 33
31 Dec. 1957	1,501	178	1,679	301	107	12	2,099
Canadian Branch (included in the above Table)							
31 Dec. 1956	58	5	63	272	—	—	335
31 Dec. 1957	66	5	71	270	—	—	341

Deaths

The Council record with sorrow the deaths of Dr. C. E. P. Brooks, Life Fellow, elected in 1913, former Secretary, Vice-President and Librarian; Dr. I. C. Browne, Councillor, elected to Student Membership in 1948 and transferred to Fellowship in 1952; Le Général E. Delcambre, Honorary Member, elected in 1932; Professor H. Ficker, Honorary Member, elected in 1950; R. G. K. Lempfert, elected in 1904, President 1930-1931; Professor C.-G. Rossby, Honorary Member, elected in 1939, Symons Gold Medallist (1953); and Professor H. U. Sverdrup, Honorary Member, elected in 1935.

The following deaths are also recorded with regret, the date of election being appended to the names: C. R. Armstrong (1955), Dr. A. W. M. Battersby (1947), Captain G. Byers (Life Fellow 1912), S. H. Ebery (1943), F. A. Henson (1951), J. H. Parry-Jones (1952), Wm. Salmond (Life Fellow 1914) and Dr. L. Sherman (Foreign Member 1952). *Canadian Branch* : A. R. Shaw (Associate 1951).

Library

A further increase in the number of individual loans, personally or by post, from the librar has occurred. A considerable number of inquiries by telephone, post and visit have been dea with.

During the year, 10 new series of journals and memoirs have been received. For two c these the *Quarterly Journal* is being sent in exchange (China and Uzbek S.S.R.); three other are included in existing exchanges and the remainder come as free gifts.

Nineteen institutions have been removed from the *Quarterly Journal* exchange or free list Two of them have agreed to purchase the *Quarterly Journal* in future.

Glazing of the shelves has been continued in the Reference and Research Room and som of the older books, in bad repair, have been rebound.

After considerable delay, satisfactory full-plate prints of cloud photographs of the Clark collection have been made, but some still present difficulties. Similar action will be taken for th selection from the Cave collection.

Staff

At the close of the year the staff consisted of Mr. M. E. Shoenberg, B.A., Assistant Secretary Mr. R. S. Read, I.S.O., M.A., B.Sc., A.R.C.S., F.Inst.P., Assistant Librarian; Mrs. A. Wallis Accounting Assistant; Mrs. W. A. Steward, Publications Clerk and Editorial Assistant Mrs. C. C. Chesley, Secretarial Assistant; Miss E. Crafts, *Weather* Clerk; and Miss E. Hooper Junior Clerk.

The Officers and Council gladly record their appreciation of the excellent manner in which the staff have carried out their duties during the past year.

Branch and Centres

Canadian Branch

Seven meetings were held in Toronto during the year in addition to the Annual General Meeting in January. The Third and Fourth National Meetings held on 3 June and 7 November were attended by representatives from all parts of Canada.

A revision of the Canadian Branch By-Laws was completed in 1957.

The Committee consisted of : President, W. L. Godson; Vice-President, R. H. Douglas; Vice-President for Canada, D. P. McIntyre; Treasurer, C. Goodbrand; Secretary, R. Lee; Councillors-at-Large, Chairman of the Montreal Centre, Chairman of the Winnipeg Centre, B. V. Benedictson, S. J. Buckler and M. Hardman.

Montreal Centre. Five meetings were held during 1957, with an average attendance of nearly thirty. On 25 January, members met in the MacDonald Physics Building, McGill University, where Walter Hitschfeld of McGill described the collection of hail reports in the Montreal area in 1956 and showed associated radar pictures. The Officers were : Chairman, T. W. R. East; Secretary, G. H. Washburn; Treasurer, D. E. McClellan.

Winnipeg Centre. Five meetings were held in 1957, with an average attendance of about twenty. The Officers were : Honorary Chairman, D. M. Robertson; Chairman, S. V. A. Gordon; Vice-Chairman, D. S. McGeary; Secretary, A. Reimer; Treasurer, P. R. Kowal.

Scottish Centre

Four meetings were held during the year at Edinburgh University. No summer meeting confined to the Scottish Centre was held because the two-day summer meeting of the Society took place in Glasgow. In March, under the auspices of the Glasgow and Edinburgh Education Authorities, Mr. N. Bradbury delivered his Popular Lecture on 'Aviation Meteorology' in Glasgow and Edinburgh.

The Committee consisted of : Chairman and Vice-President for Scotland, Mr. J. R. Atkinson; Secretary and Treasurer, Mr. D. H. McIntosh; and eleven other Fellows.

Manchester Centre

Five meetings were held during the year at the University of Manchester. The attendance at these meetings averaged nearly twenty, including two very regular student members. A sixth meeting which should have been held in November was postponed until March 1958. In March 1957 another Popular Lecture was given under the auspices of the Manchester Education

Committee at the Manchester Training College. The lecture was delivered by Mr. N. Bradbury on ' Aviation Meteorology ' and was attended by about 300 sixth-form pupils. The Committee consisted of : Chairman, Professor P. R. Crowe; Secretary, Mr. N. K. Horrocks; Assistant Secretary, Dr. H. P. Palmer; Treasurer, Mr. G. Reynolds; and ten other Fellows, including the late Dr. I. C. Browne.

Representatives

The Society's representatives on other scientific bodies were :

Royal Society Committees
Gassiot Committee, President; *British National Committee for Geodesy and Geophysics*, Sir Graham Sutton (1952-57), T. W. Wormell (1955-60); *British National Committee for Physics*, F. Pasquill (1955-60).

Institute of Physics Advisory Committees
Journal of Scientific Instruments, H. L. Penman; *British Journal of Applied Physics*, G. D. Robinson.

Cambridge University Meteorological Committee
Professor P. A. Sheppard.

Royal Astronomical Society
Geophysical Committee, G. D. Robinson.

Advisory Committee for the Meteorological Office, Edinburgh
Sir Charles Normand.

British Glaciological Society
Professor Gordon Manley.

Awards

The following awards were presented at the Annual General Meeting on 17 April :

Symons Memorial Gold Medal for 1957

Professor Erik Palmèn, D.Ph., Institute of Meteorology, University of Helsinki, a member of the Academy of Finland, for his outstanding work in the field of synoptic aerology.

Darton Prizes for 1956

Home Awards :
1st Prize : Mr. A. J. Drummond.
2nd Prize : Dr. J. F. Nagel.

Canadian Awards :
1st Prize : Mr. B. W. Boville and Mr. M. Kwizak.
2nd Prize : Mr. G. A. McKay.

Scientific Activities Fund

During the year the following grants were made :

Prizes for the *Weather* Essay competition held to mark the occasion of the tenth year of publication.

Overseas delegates, towards subsistence expenses for attending the joint symposia with the Royal Astronomical Society on ' Planetary atmospheres and convection in rotating fluids ' held in May.

Mr. J. Hallett and party towards the cost of an expedition to ice caves in the Pyrenees to study the micro-structure of the exceptionally large ice crystals to be found there.

Dr. M. H. Rogers and Dr. G. F. Walton towards travelling expenses in attending the U.G.G.I. Conference held at Toronto in September.

Field Studies Council towards the expenses of a pioneer meteorological vacation course on ' The weather and flight,' mainly for members of flying and gliding clubs, held in July 1957, at the new field centre at Preston Montford, Nr. Shrewsbury.

In addition the following grant was approved, payment to be made when the work starts :

Mr. T. J. Chandler, towards the cost of the petrol for use in carrying out a programme of car traverses in the Lea Valley, investigating the local climate variations there.

British Rainfall Organization Fund

By arrangement with the St. Pancras Borough Council the Observing Station at 62 Camden Square was transferred to a nearby site, suitably fenced, in the small park in Camden Square.

On 8 August the plaque which, as already recorded, had been affixed to the property at 62 Camden Square, was unveiled by the Mayor of St. Pancras, Councillor T. J. Redman. The President, Dr. R. C. Sutcliffe, F.R.S., Mr. Ian Kirkpatrick, Chairman of the British Rainfall Organization Committee, and other Officers and members were present. The party then proceeded to the new observing station which was formally opened by the President. The ceremony was followed by a luncheon at which the Director-General of the Meteorological Office, the Mayor, and other officials of the St. Pancras Borough Council were present as guests.

As had been agreed, action was taken to sell the property at 62 Camden Square and the legal formalities were in process of being completed at the end of the year. In the meantime observations were continued at the old site at 62 Camden Square to provide an overlap period.

Finance

It will be seen that there is a deficit this year of £80 as compared with one of £253 last year. This slight improvement is, however, entirely due to the exceptionally heavy sales of back numbers of the *Quarterly Journal*, which, as shown, amounted to £1,122 as compared with £486 in the previous year.

Were it not for this non-recurring item the financial position would have been very serious, particularly in view of the decision by the Royal Society not to make any Grant-in-Aid of Publications, which in the previous year amounted to £500.

The Society's claim to a refund of income tax on covenanted subscriptions is still pending and, in view of the uncertain position, no provision has been included in the Income in respect of this item.

The Royal Society allocated to the Society the sum of £300 for the Library, and the receipt of this grant is acknowledged with gratitude.

The healthy position of the Society is reflected in its record Membership and the flourishing condition of its publications, as indicated elsewhere in the Report. It is hoped that the increases in membership fees and the *Quarterly Journal* subscription, as from January 1958, will result in a substantial improvement in the financial position of the Society next year, and leave some margin for developing its activities.

RECEIPTS AND PAYMENTS OF SPECIAL FUNDS FOR 1957

	Balance at 31.12.56	Income for 1957	Expenditure for 1957	Balance at 31.12.57
	£	£	£	£
Awards Fund	10	—	—	10
British Rainfall Organization Fund	24	192 (a)	144	72
Life Composition Fund	505	288 (b)	733 (c)	60
Napier Shaw Memorial Fund	120	72	—	192
Royal Society Reprints Scheme	1	22	7	16
Scientific Activities Fund	135	172	220	87
Staff Pension Fund	541	727 (d)	563 (e)	705
Symons Memorial Fund	44	36	51	29
Hampton Brown Fund	1,000	9	995 (f)	14
	£2,380	£1,518	£2,713	£1,185

(a) Includes £51 rent from 62 Camden Square; (b) Includes £58 – balance on Sales of Investment; (c) Made up of £200 transfer from "A" Account and £533 purchase of £500 Bowater Paper Corporation Ltd. Stock; (d) Includes transfer of 15% of Salaries £408 and £197 balance on Sales of Investment; (e) Made up of £533 purchase of £500 Bowater Paper Corporation Ltd. Stock, £30 Application for £150 B.P. 6% Deb. Stock; (f) Includes £92 purchase of 250 "A" Ordy. Marley Tile (Holding) Co. Ltd. and £903 purchase of 500 £1 Ordy. Hawker Siddeley Group Ltd.

Examined and found correct
27 March 1958

BALL, BAKER & CO.,
Chartered Accountants

1956 £	£		£	£
		ACCUMULATED FUND—		
		Excess of Assets over Liabilities at 1 Jan.		
	12,487	1957	12,234	
	508	*Deduct* Library Equipment Fund ..	463	
	11,979		11,771	
	—	*Deduct* Loss on Sale of Investments ..	389	
	11,979		11,382	
	253	*Deduct* Excess of Expenditure over Income	79	
11,726				11,303
508		Library Equipment Fund		463
		CURRENT LIABILITIES—		
	710	Creditors and Accrued Charges—	330	
		£ Amounts Received in Advance— £		
	683	Publications 1,039		
	334	Subscriptions 426		
	1,017	—	1,465	
	1,560	Due to Bankers	385	
3,287				2,180

We have examined the above Balance Sheet and annexed Income and Expenditure Account which in our opinion respectively give a true and fair view of the state of the Society's affairs as at 31 December 1957, and of its income and expenditure for the year ended on that date.

Spencer House,
South Place,
LONDON, E.C.2. BALL, BAKER & Co.
27 March 1958 *Chartered Accountants.*

1956 £	£			£	£
		FIXED ASSETS—			
		Freehold Property – Estimated value (in 1925) of the Society's House, 49			
5,375		Cromwell Road			5,375
		Furniture and Equipment—			
			Accumulated cost	Additions during year	Accumulated Depreciation	Net
	1,223	General	1,536	—	428	1,108
	508	Library	606	—	143	463
1,731			£2,142	—	£571	£1,571
						1,571
		(No amount has been included for the value of the Library and the stock of publications)				
		INVESTMENTS—				
		Valued at Market Price 31.12.54, with additions since at cost—				
	924	(£1,400 2½% Consolidated Stock) ..			—	
	1,206	£1,250 4% Consolidated Stock 1957 or after			1,206	
	796	(£900 3½% Conversion Loan 1961 or after)			—	
	206	£200 4% Funding Stock 1960/90 ..			206	
	645	£649.1.7 Government of Australia 4% Registered Stock 1955/70			645	
	2,030	£2,000 Government of Australia 4% Registered Stock 1966/68			2,030	
	—	£100 Burmah Oil Co. Ltd. Ordinary Stock			562	
	—	£221 Guest, Keen & Nettlefolds Ltd. Ordinary Stock			612	
	—	£200 Courtaulds Ltd. Ordinary Stock ..			368	
	—	200 Marks & Spencer Ltd. "A" Ordinary 5/- Shares			506	
5,807						6,135
		(Market Value 31.12.57 £4,746)				
		(Market Value 31.12.56 £4,726)				
		CURRENT ASSETS—				
50		Stock of Stationery				15
		Debtors—				
		£ *Proceedings Toronto Meteorological Conference* 1953 ..		£ 43		
	54					
	804	Subscriptions		291		
	559	Publications		582		
	1,417			916		
	150	*Less* Provision for bad and doubtful debts		150		
	1,267			—	766	
	50	Payments in advance			58	
	1,241	Deposit at Post Office and Cash in Hand			26	
2,558						850

GENERAL

INCOME AND EXPENDITURE ACCOUNT

EXPENDITURE

1956 £	£	£		£	£	£	£
			ESTABLISHMENT—				
	27		Water Rates			25	
	270		Cleaning Wages and Materials			283	
	27		Insurance			22	
	211		Lighting and Heating			183	
	170		Repairs and Maintenance			145	
	116		Depreciation of Furniture and Equipment			115	
821							773
			ADMINISTRATION—				
	2,645		Salaries			2,745	
	388		Contribution to Staff Pension Fund			408	
	95		Printing			39	
	160		Stationery			308	
	274		Postage, Carriage and Packing			304	
	76		Telephone			82	
			Audit and Accountancy Fees—				
	105		Royal Meteorological Society			105	
	31		*Weather* Magazine			31	
	32		Sundries			45	
3,806							4,067
			PUBLICATIONS, ETC.—				
	3,647		*Quarterly Journal*			3,978	
	315		Illustrations			327	
	—		*Cloud Study*			155	
	300		Reprints of Papers			255	
	8		*Monthly Weather Report*			37	
	994		Members' copies of *Weather*			985	
	2		Second-hand Journals			61	
5,266							5,798
			LIBRARY—				
	486		Salary			486	
	192		Books, Bindings, etc.			162	
	45		Depreciation on Fixtures and Fittings			46	
723							694
			MEETINGS' EXPENSES—				
		88	London		101		
		90	Travelling Expenses	106			
		—	*Less* reimbursed by Air Ministry	6			
	178	—		—	100		
						201	
	40		Scotland			40	
	30		Manchester			30	
248							271
28			PROVISION FOR BAD AND DOUBTFUL DEBTS—				37
			GRANTS AND PRIZES—				
	100		Scientific Activities Fund			100	
	40		Grant to Field Studies Council			40	
140							140
£11,032							£11,780

UND

OR THE YEAR ENDING 31 DECEMBER 1957

INCOME

1956 £	£	£		£	£	£
			SUBSCRIPTIONS, ETC.			
	5,216		Subscriptions		5,418	
	98		Entrance Fees		105	
	11		Donations		22	
	5,325				5,545	
	167		*Less*: Adjustments for Lapsed Membership (By-law 40)		110	
5,158						5,435
			PUBLICATIONS—			
	2,281		Sale of Publications – Current *Q.J.*		3,079	
	486		Sale of Publications – back numbers *Q.J.*		1,122	
	—		Sale of *Cloud Study*		190	
	351		Reprints		300	
	514		Advertisements		525	
			Proceedings Toronto Meteorological Conference 1953—			
	45		Sales etc.		15	
	3,677				5,231	
	500		Grant from Royal Society (excluding Library)		—	
4,177						5,231
			INVESTMENT INCOME—			
	260		Interest on Government Stocks (Gross)		215	
	—		Interest on Industrial Securities (Gross)		27	
		254	Rent of Maisonettes	282		
		83	*Less*: Rates	127		
	171				155	
431						397
			PHOTOGRAPHS—			
	32		Sale of Cloud Postcards		17	
		119	Clarke and Cave Copyright Fees	91		
		3	*Less*: *Reproduction Costs*	—		
	116				91	
148						108
			LIBRARY—			
	400		Grant from the Royal Society		300	
	50		*Sale of old Library Books*		—	
450						300
			AMOUNTS RECEIVED FROM OTHER FUNDS—			
	200		Life Composition Fund		200	
	15		British Rainfall Organization Fund (for Administration)		30	
215						230
200			Grant from *Weather*			—
253			BALANCE, BEING EXCESS OF EXPENDITURE OVER INCOME—			79
£11,032						£11,780

VALUATION OF INVESTMENTS AT 31 DECEMBER 1957

Market Value 31.12.56			*Market Value 31.12*	
£	£		£	£
		*General Fund**		
	735	(£1,400 2½% Consols)	—	
	956	£1,250 4% Consols x.d.	869	
	635	(£900 3½% Conversion Loan 1961 or after)	—	
	175	£200 4% Funding Stock 1960/90	173	
	535	£649.1.7 Government of Commonwealth of Australia 4% Registered Stock 1955/70	526	
	1,690	£2,000 4% Government of Commonwealth of Australia 4% Registered Stock 1966/68 x.d.	1,670	
	—	£100 Burmah Oil Co. Ltd. Ordinary Stock	356	
	—	£221 Guest Keen & Nettlefold Ltd. Ordinary Stock	519	
	—	£200 Courtaulds Ltd. Ordinary Stock	213	
	—	200 Marks & Spencer Ltd. "A" Ordinary 5/– Shares x.d.	420	
4,726				4,7
		Scientific Activities Fund		
	176	£250 3½% War Stock 1952 or after	158	
	71	£100 3½% Conversion Loan 1961 or after	63	
	825	£1,000 4% Trinidad Government Stock 1973/76	765	
1,072				9
		Staff Pensions Fund		
	564	(£800 3½% War Stock 1952 or after)	—	
	211	(£300 3½% Conversion Loan 1961 or after)	—	
	604	(£1,150 2½% Consolidated Stock)	—	
	689	£900 4% Consolidated Stock 1957 or after x.d.	626	
	413	£500 4% Trinidad Government Stock 1973/76	383	
	465	£600 3½% Treasury Stock 1979/81	429	
	—	£500 Bowater Paper Corporation Ltd. 5¾% Convertible Unsecured Loan Stock 1978/82	445	
	—	£200 English Electric Co. Ltd. Ordinary Stock	475	
	—	£150 Turner & Newall Ltd. Ordinary Stock x.d.	413	
	—	£150 British Petroleum Co. Ltd. 6% Convertible Debenture Stock 1976/80 (£20 paid)	38	
2,946				2,8
		Life Composition Fund		
	420	(£800 2½% Consolidated Stock)	—	
	564	(£800 3½% Conversion Loan 1961 or after)	—	
	268	£350 4% Consolidated Stock 1957 or after x.d.	243	
	775	£1,000 3½% Treasury Stock 1979/81	715	
	—	£500 Bowater Paper Corporation Ltd. 5¾% Convertible Unsecured Loan Stock 1978/82	445	
	—	£200 Imperial Chemical Industries Ltd. Ordinary Stock	383	
	—	£100 Canadian Eagle Oil Company Ltd. Ordinary Shares n.p.v.	243	
2,027				2,0
		*British Rainfall Organization Fund***		
	529	£750 3½% War Stock 1952 or after	473	
	2,122	£3,097.10.0 British Transport 3% Guaranteed Stock 1978/88	1,889	
	76	£100 4% Consolidated Stock 1957 or after	70	
	233	£300 3½% Treasury Stock 1979/81	215	
2,960				2,6
		Napier Shaw Memorial Fund		
	247	£350 3½% Conversion Loan 1961 or after	221	
	306	£400 4% Consolidated Stock 1957 or after x.d.	278	
553				4
		Symons Memorial Fund		
	458	£650 3½% Conversion Loan 1961 or after	410	
	153	£200 4% Consolidated Stock 1957 or after	139	
611				5
		Hampton Brown Fund		
	—	500 Hawker Siddeley Group Ltd. Ordinary £1 Shares x.d.	769	
	—	250 Marley Tile (Holding) Co. Ltd. "A" Ordinary 5/– shares	86	
—	—			8
£14,895				£15,1

* General Fund also includes the Freehold of 49 Cromwell Road, S.W.7.

** British Rainfall Organization Fund also includes the Freehold of 62 Camden Square, N.W.1.

Examined and securities seen.
27 March 1958

BALL, BAKER & CO.,
Chartered Accountan

Proceedings at meetings of the Society

Symons Memorial Lecture, 2 April 1958

Prof. C. W. Allen, Professor of Astronomy in the University of London, delivered the Symons Memorial Lecture, his subject being 'Solar radiation.'

Annual General Meeting, 23 April 1958

Professor P. A. Sheppard, B.Sc., F.Inst.P., in the Chair. The minutes of the Annual General Meeting held on 17 April 1957 were confirmed and signed.

In presenting the Report of the Council for the year 1957 the President referred to the main items of interest.

As explained in the Report, in order to put the Society's finances on a sound footing, an increase in subscriptions to Members and to the *Quarterly Journal* was unavoidable. Council's proposals had been approved at a Special General Meeting.

The year was marked by a most successful programme of meetings which included an international symposium. The Summer Visit to the Atomic Energy Research Establishment at Harwell was held at the invitation of Sir John Cockcroft. The fourth Two-Day Summer Meeting was held at the University of Glasgow and our best thanks were due to Professor P. I. Dee, F.R.S., Mr. J. R. Atkinson and the Scottish Committee for the excellent arrangements.

The Society's publications had maintained their high standard and thanks were due to the Editor, Editing Committee, and the *Weather* Editing Committee. A new venture which was very successful was the publication, under the auspices of the Society, of *Cloud study : a pictorial guide*, by Mr. F. H. Ludlam and Dr. R. S. Scorer. This book could be considered to be one of the most successful texts in popular meteorology and filled a real need.

The membership of the Society was satisfactory and once again showed a small increase over the previous year. The Canadian Branch and the centres in Scotland and Manchester had continued to make good progress.

The President referred to the heavy loss to the Society by the death of a number of prominent members : the Treasurer for the year under review, Dr. J. S. Farquharson, was killed in a tragic accident.

While the small resources of the Scientific Activities Fund hampered the scope of the activities which could be supported, a number of awards had been made to encourage meteorological research.

An important change had been made in the arrangements for maintaining, from the British Rainfall Organization Fund, the Observing Station at 62 Camden Square, which had been transferred to a nearby site in the gardens of Camden Square. The continuity of the observations was thus assured and the Society relieved of the heavy upkeep costs for 62 Camden Square, which had been sold.

The Treasurer, Mr. B. C. V. Oddie, after referring to the sad death of Dr. Farquharson reported on the financial section and explained that while the deficit on the year's working was only £79 instead of £1,000 as originally estimated, this was entirely due to the exceptionally heavy sales of back numbers of the *Quarterly Journal* which amounted to £1,122. Were it not for this non-recurring item of revenue the financial position of the Society would have been very serious and the increases in subscriptions, as made, were therefore fully justified.

The President moved that the Report be received and adopted and that it be printed in the *Quarterly Journal*. The motion was carried unanimously.

Instr. Cdr. J. R. Thorp proposed a vote of thanks to the President and Council for the year 1957 and this was seconded by Mr. F. H. Ludlam.

The Treasurer proposed the following motion on investments, submitted by the Counc in accordance with By-Law 86 :

> ' That a sum of up to £3,000 may be invested in non-Trustee stocks during the period of twelve months until the next Annual General Meeting.'

This motion was seconded by Mr. J. M. Craddock and carried *nem con.*

The President then announced the election of the following five eminent meteorologis into Honorary Membership :

Professor Tor Bergeron, Symons Medallist, Professor of Meteorology, University of Uppsala;

Professor Sir David Brunt, F.R.S., Fellow since 1918, former President and Symons Medallis

E. Gold, Esq., C.B., D.S.O., F.R.S., Fellow since 1908, former President and Symons Medallis

Professor Sverre Petterssen, Professor of Meteorology, University of Chicago;

Sir George Simpson, K.C.B., F.R.S., Fellow since 1905, former President and Symons Medallis

Sir David Brunt, Mr. E. Gold and Sir George Simpson were present and received amids acclamation the Diplomas of Honorary Membership from the hands of the President.

The President then announced the following awards :

(a) *Buchan Prize* in respect of the period 1953–1957 :

To Richard Mead Goody, M.A., Ph.D., for his outstanding contributions to the theor and observation of the absorption and emission of radiation in the atmosphere.

(b) *Hugh Robert Mill Medal and Prize for 1957* :

To Leo Claude Wallace Bonacina, a friend and colleague of H. R. Mill, whose interest i precipitation in Britain has covered a period of more than 50 years.

(c) *Darton Prizes for 1957* :

Home Awards : (1) Mr. J. W. Hutchings for his paper ' Water-vapour flux and flux-diver gence over southern England : summer 1954 ' (*Q.J.*, p. 30, 1957), (2) Mr. I. F. Long for his paper ' Instruments for micro-meteorology ' (*Q.J.*, p. 202, 1957).

Canadian Awards : Dr. T. W. R. East for his paper ' An inherent precipitation mechanism in cumulus clouds ' (*Q.J.*, p. 61, 1957), (2) Mr. J. Clodman for his paper ' Anisotropic high-level turbulence ' (*Q.J.*, p. 116, 1957).

Professor P. A. Sheppard, B.Sc., F.Inst.P., then delivered the Presidential Address, his subject being ' Transfer across the earth's surface and through the air above.' Mr. J. S. Sawyer proposed a vote of thanks to the President for his Address and asked that he would allow it to be printed in the *Quarterly Journal.* Mr. H. Charnock seconded the vote of thanks. The meeting was declared closed at 7.30 p.m.

Additional Meeting, 13 May 1958

A Joint Meeting with the National Society for Clean Air was held at Agriculture House, S.W.1., with an attendance of about 120 members of both Societies and guests. The meeting consisted of two sessions at which the Chairman was respectively Dr. R. Lessing, President of the National Society for Clean Air and Dr. R. C. Sutcliffe, F.R.S., Vice-President. The opening speakers were : Mr. C. J. Regan (Chairman, Atmospheric Pollution Research Committee) on

' Progress in atmospheric pollution research '; Dr. W. C. Turner (M.O.H., Poplar) on ' The introduction of smoke-control areas '; Mr. R. G. Veryard (Meteorological Office) on ' Climatological aspects of air pollution ' and Mr. N. G. Stewart (Harwell) on ' Radioactivity in the atmosphere : its origin and measurement.'

A fuller account of the meeting will appear in *Weather* and a report will be published in *Smokeless Air*.

Ordinary Meeting, 21 May 1958

The following candidates were declared to have been elected on 23 April by the Council :

Fellows

Alcock, George Eric Deacon, F.R.A.S., 55 Broadway, Farcet, Peterborough, Northants.
Anderson, Michael Paul, 36 Old Laira Road, Plymouth, Devon.
Ardley, Stanley Edward, 64 Downlands Avenue, Broadwater, Worthing, Sussex.
Henderson, Geoffrey Stewart Arama, 23a Spencer Road, East Molesey, Surrey.
Hill, Herbert Edward, 7 Cotton Road, Potters Bar, Middx.
Leaf, Geoffrey Glanville, B.Sc., 305 Beverley Road, Anlaby, Hull, Yorks. (*transfer from Student Membership*).
Mula, Abdel Cadir Mohammed Fadlel, B.Sc., Sudan Meteorological Service, Khartoum, Sudan.
Rampling, Brian Malcolm Laurel, 206 Park Street Lane, Nr. St. Albans, Herts.
Robinson, John Godfrey, B.Sc., Hill View, Bucklebury, nr. Reading, Berks. (*transfer from Student Membership*).

Foreign Members

Thor, Charles, M.S., Department of Geology, The City College of New York, 139th Street and Convent Avenue, New York 31, N.Y., U.S.A.
Worth, James Judson Blackley, M.S., Bendix Aviation Corporation, Systems Division, Ann Arbor, Michigan, U.S.A.

Student Member

Ewulu, Godwin Ifeanyi, Department of Meteorology, Imperial College, Exhibition Road, London, S.W.7.

The following candidates were then declared elected that day by the Council :

Fellows

Adeoye, Adebayo Babaniji, 56 Ivy Road, Cricklewood, London, N.W.2. (*transfer from Associate Membership*).
Crewdson, Capt. John, A.R.Ae.S., ' Stone Court,' Smallfield Road, Horley, Surrey.
Ebdon, Robert Andrew, c/o Cherry Lodge, Danaway, Sittingbourne, Kent.
Pedgley, David Eric, B.Sc., 228 Tylecroft Road, Norbury, London, S.W.16.
Reed, Wilfred Edward, 94 Chiltern Avenue, Bushey, Herts.
Santer, Walter James Frederic, Greystones, Gidleigh, Chagford, Devon.
Wiggett, Peter John, B.Sc., 16a West End Gardens, Northolt, Greenford, Middx.

Foreign Members

Hosler, Charles Robert, M.S., U.S. Weather Bureau, Special Projects Section, OA58, 24 & M Streets, N.W., Washington 25, D.C., U.S.A.
Pack, Donald Henry, Special Projects Section, Office of Meteorological Research, U.S. Weather Bureau, Washington 25, D.C., U.S.A.
Sasaki, Yoshikazu, Ph.D., Department of Oceanography, A & M College of Texas, College Station, Texas, U.S.A.

Student Members

Grice, Anthony William, 12 Highfield Avenue, Langwith Junction, nr. Mansfield, Notts.
Welch, Michael Robin, 20 Hartington Road, Aldeburgh, Suffolk.

Canadian Branch

Fellows

East, Thomas William Russell, Ph.D., 5838 Coobrook Avenue, N.D.G., Montreal, Que Canada (*transfer from Associate Membership*).

Evenson, Allan Arnold, M.A., 9825 N.E. 22nd Bellevue, Washington, U.S.A. (*transfer fro Associate Membership*).

Kendall, George Roland, M.A., 260 Richmond Street West, Toronto, Ontario, Canad (*transfer from Associate Membership*).

Keyte, Freeman Kilbourne, B.A., Aviation Forecast Office, Municipal Airport, Calgary, (DIS) Alberta, Canada.

Thomas, Morley Keith, M.A., 315 Bloor Street West, Toronto 5, Ontario, Canada (*transfe from Associate Membership*).

Associates

Brown, Nancy Ann, B.S., Central Analysis Office, Montreal Airport, Dorval, P.Q., Canada.

Charnley, Elizabeth May, B.A., Central Analysis Office, Montreal Airport, Dorval, P.Q. Canada.

Davies, Alfred Franklin, B.Sc., B.D., M.A., Box 466, Gander, Newfoundland.

Elsley, Elmer MacFadden, B.A., Central Analysis Office, Montreal Airport, Dorval, P.Q. Canada.

Finlay, Patrica Gertrude, B.S., Central Analysis Office, Trans-Atlantic Administration Bldg. Montreal Airport, Dorval, P.Q., Canada.

McLaughlin, Violet Domikia, B.Sc., Central Analysis Office, Montreal Airport, Dorval, P.Q. Canada.

The meeting took the form of a discussion on ' The dynamical state of the upper atmosphere ' and consisted of two sessions. The opening speakers were : Mr. R. J. Murgatroyd (Meteor- ological Research Flight, Farnborough) on ' The climatology and radiation balance of the 30 to 100 km region of the atmosphere '; Mr. E. L. Neufeld (Jodrell Bank Experimental Station) on ' Unsteady motions in the upper atmosphere '; Dr. R. S. Scorer (Department of Mathematics, Imperial College) on ' Development in the upper atmosphere '; Mr. J. S. Sawyer (Meteorological Office) on ' General circulation of the stratosphere ' and Mr. T. V. Davies (Department of Mathematics, King's College, London) on ' Magnetodynamic circulations.'

rofessor Abbe and the isobars: the story of Cleveland Abbe, America's first weatherman. By Truman Abbe. New York (Vantage Press), 1955. Pp. x, 259; 6 Illustrations; 14 Plates. Np.

The publication of a biography of a meteorologist is a rare event – unique so far as I know. Consequently ıe life of Cleveland Abbe, written by his son Truman Abbe, has a special attraction for all interested in the evelopment of meteorology and meteorological organization in the U.S.A. in the latter part of the nineteenth entury. The book would have gained technically if it had been written by a meteorologist but it would robably thereby have lost much of the intimate human interest which Dr. Abbe was in a position to give ; he wrote it after his retirement from medical practice and it was 40 years after Cleveland Abbe's death 28 Oct. 1916) by the time it was published.

The book makes no pretence at a comprehensive account of Abbe's meteorological work; that does nter, largely owing to the assistance of J. C. Alter of the U.S. Weather Bureau. But the book is substantially he life story of a man of unusual lineage and character, led into meteorology by a number of incidents not umanly planned. He might have lived and died an astronomer but for the decrepit state, in 1868, of an stronomical observatory at Cincinnati and the lack of funds to restore it. Abbe, frustrated in his astronomical mbitions which were pitched high after two years at Pulkova under Otto Struve, began in 1869 the collection f weather reports from a network of stations and the issue of a *Daily Weather Bulletin*.

Largely as a result of this experiment at Cincinnati, Congress passed a Bill authorizing the Secretary f War to collect observations and issue storm warnings for the Great Lakes and the Atlantic Coast. The Bill became law on 9 Feb. 1870, less than two months after it was introduced into Congress. 'This was emarkable speed for a scientific bill.'

Abbe had expressed the view that meteorologists would do the job better than Army Officers. 'It would be a pity to see the country saddled with an inefficient meteorological office . . . .' But within a year he was invited by the Chief Signal Officer, General Myer, to become forecaster in the service at a salary f $3,000 a year from 3 Jan. 1871. Six months later the salary was raised to $3,750 and on 1 July 1872 to $4,500, the highest salary but one in the government service. This was regarded as more or less outrageous, perhaps not surprisingly, as then, and for long afterwards, meteorology was looked upon as a little below the Cinderella of the sciences. General Myer, a man in advance of his time, as Army Generals can be, was forced to make a cut.

Twenty years later the weather service was transferred from the Signal Corps to the Department of Agriculture and became the Weather Bureau. There, 'friction between the scientific mind and bureau method was not infrequent. At one time a general order . . . demanded strict observance of office hours; 9.00 a.m. to 4.30 p.m. – no more, no less . . . . it was exasperating not to be allowed to continue or finish some train of thought that he was working on at 4.30 p.m.' A change of President from Benjamin Harrison to Grover Cleveland had the result that the 'the scientific group, Abbe, Bigelow, Wylie and Marvin were reduced in pay and rank.' That did not prevent Abbe from doing his best 'to uphold the dignity and the value of the Weather Bureau and of science as opposed to chicanery.' He certainly did this when he collected, translated where necessary and published the comprehensive collection of papers in the three successive volumes entitled *Mechanics of the earth's atmosphere*. He thereby placed at the disposal of English-speaking meteorologists the works of the many able mathematicians who had attacked some of the fundamental problems of the dynamics and thermodynamics of the atmosphere, at a time when there was no textbook on these two subjects in any language.

Fortunately, too, Abbe was not deflected from his efforts, continued throughout the 23 years of his editorship of the *Monthly Weather Review*, 1893-1916, to stimulate meteorological science both by his own contributions and by the encouragement and the hospitality which he gave without stint to young meteorologists from Europe. One of these was H. N. Dickson who, by a fortunate coincidence, as President of the Royal Meteorological Society, presented the Symons Gold Medal to Abbe in 1912. It was a memorable occasion, the first and so far the only time the Medal has been awarded to an American meteorologist; Abbe was so overcome by emotion that he could not finish his halting words of thanks and appreciation.

Abbe, descendant on the one side of New England farmers and on the other of Kentish yeomen, was born on 3 Dec. 1838. He was twice married and had three sons, one of whom was also a meteorologist in the Weather Bureau.

E.G.

Climatology – treated mainly in relation to distribution in time and space. By W. G. Kendrew. Oxford (Clarendon Press), 1957. Pp. xv, 400; 16 Plates; 131 Figs; Tables; Bibliography. 42s.

The first edition of this book published in 1949 was really a third but extensively rewritten edition of Kendrew's well known *Climate*. The change of title was intended to cover a more comprehensive survey of the physical causes which underlie the various manifestations of climate. This was all to the good but it seemed that the author had found it difficult to keep abreast of advances in the science of meteorology. In the second edition of *Climatology*, the author has certainly endeavoured to incorporate new knowledge and new ideas, e.g., in regard to jet streams and 'blocking' anticyclones, but the result is still a somewhat disappointing mixture of an ancient and modern treatment of a subject which nowadays calls for a dynamic and synoptic approach as well as a statistical approach.

In fact, although there are some major additions, the mixture is very much the same as before. Thh are still six parts, of which the first three deal with the meteorological elements: insolation and temperatu atmospheric pressure and winds; vapour and its condensation (including rain, cloud, sunshine and visibili and the last three with the climate of different regions: mountain and plateau climate; the weather of t westerlies; some climatic types (Sudan, Mediterranean and westerlies). Most of the new material rela to the higher troposphere but is mainly descriptive and, in spite of this welcome attention to the upper a the treatment of the subject as a whole is still two-dimensional rather than three-dimensional. Indee most modern climatologists – certainly those trained in the discipline of meteorology – would not acce the author's contention that ' Climatology is concerned essentially with the weather on or near the surfa of the earth ' or that ' An adequate treatment of the upper air is the concern of meteorology rather than climatology.'

The short but useful bibliography has only partly been brought up to date; references to importa studies by workers in countries outside Europe and North America are not included. The index is still source of irritation in that there is too much grouping of entries under main elements, e.g., the sub-headin and page references under temperature take up nearly half a page ! But to go on and list some of the sm errors, out-dated statistics and other minor shortcomings, would be misleading as the book will doubtle remain a standard in its class for many years to come.

The sixteen photographic plates are a most pleasing feature of this book and the whole production well up to the high standard which we are now accustomed to expect from the Clarendon Press at Oxfor For a volume of this size by such a well-known authority, it is inevitable in these days of rising costs th the price would be high but, in the opinion of the reviewer, the sum of 42s. is a bit too high. However, fo those who wish to have on their shelves a valuable reference book with its wealth of information, for tho students who desire to acquire a good background knowledge of the subject, this new edition of Kendrew *Climatology* may be regarded as fair value for money.

R.G.V.

The physics of clouds. By B. J. Mason. Oxford (Clarendon Press), 1957. Pp. xx, 481; 166 Figs.; 54 Table 70s.

This substantial volume is the first in a new series entitled ' Oxford monographs on meteorology under the general editorship of Prof. P. A. Sheppard. As the author says in his Preface, the emphasis i upon the microphysical processes in the study of which he and his collaborators have taken a leading rôle in recent years.

' The large-scale physics of clouds ' is the ambitious title of a brief elementary introduction b F. H. Ludlam confined to types of clouds but serving as the vehicle for some excellent cloud photographs Thereafter for the first six chapters we remain firmly involved in microphysical processes. Surprisingly considering the title of the book, the first chapter is devoted to the spontaneous condensation of water from the vapour, a process demanding high supersaturations such as never occur in cloud formation. The second and third chapters are concerned with the nuclei of condensation and their growth into cloud droplets and the two subsequent chapters with ice-forming nuclei and the growth of ice crystals. This leads logically to the sixth chapter which traces the further growth of particles to precipitation size. The treatment is very thorough and these chapters will form an excellent reference source but the reader is sometimes swamped by the mass of detail and the clear thread of the argument is obscured. The author says ' I have aimed at being critical rather than exhaustive ' but it seems to the reviewer that in some parts of these chapters the target has been widely missed.

The author then deals soberly and realistically with the subject of artificial stimulation of precipitation and very competently with radar studies of precipitation. Finally, and it is good to see, the subject of thunder- storm electricity, so often treated in isolation, is dealt with as a part of cloud physics with due regard to meteorological as well as electrical evidence.

In two appendices the collection efficiencies of water drops and the physical properties of freely falling raindrops are discussed.

The bibliography, which is up-to-date and comprehensive, is a valuable feature of a book which can be unreservedly recommended as a reference book for the research worker, but the physics student may rightly feel that rather more digesting could have been done for him.

With these publishers it is almost superfluous to say that the book is excellently bound and reproduced and almost entirely free from typographical errors.

R.F.J.

Dynamical and physical meteorology. By G. J. Haltiner and F. L. Martin. New York (McGraw-Hill), 1957. Pp. xi, 470; 247 Figs.; Tables; 2 Plates. 75s.

Twenty years or more ago the most widely used textbook published in the English language for students of theoretical meteorology was probably Professor Brunt's *Physical and dynamical meteorology.* Much has been written in many languages on theoretical meteorology since then. The war and post-war years have, in particular, produced several excellent textbooks on dynamic meteorology. Among others which students have found useful one might mention those of Haurwitz, Holmboe and Forsythe, Panofsky and Petterssen's *Weather analysis and forecasting.*

The most recent of these textbooks, *Dynamical and Physical meteorology* by Professors Haltiner and Martin of the U.S. Naval Postgraduate School, provides the student with an excellent up-to-date development of the subject.

Although five chapters are devoted to radiation, the role of physical meteorology in the book is a minor one. Dynamic meteorology is the major theme; in addition to the conventional material it takes in the related topics of diffusion of heat, water vapour and atmospheric pollutants.

The level of mathematics is that of elementary differential and integral calculus, including vector algebra. The first chapter of the book constitutes a review of vector operations. This is most useful to the student who may not feel immediately at home with the vector approach to the subject. The vector method is adopted generally and although there are strong arguments for its use at post-graduate level for the resulting simplification in mathematical expression it is not always so simply understood by the less well-equipped student of meteorology. There are occasional passages in the book which flavour of the somewhat academic treatment of Holmboe and Forsythe. Broadly speaking, however, the emphasis is on a practical exposition of the development of dynamic meteorology from first principles to the most recent stages reached by research.

After the introductory chapter on vector methods the book proper commences with thermodynamics of dry and moist air, hydrostatic equilibrium and vertical stability and convection. A few all too brief pages on cloud physics are included in these chapters. Then follow the five chapters on radiation, followed by chapters on the equations of motion, horizontal frictionless flow, variation of wind and pressure in the vertical, and in the friction layer. Later are chapters on diffusion, frontal surfaces, the mechanism of pressure change, vorticity and perturbation theory. The work closes with two chapters which will be found to be the best part of the book for the contemporary meteorologist, on dynamic forecasting by numerical methods and, finally, on the general circulation. The latter is one of the best reviews of this wide subject to be found.

Although the book's main purpose is to assist the teaching of basic principles it will be found of value, not only as an ally to the student, but as a guide to his teacher and a useful reference in less familiar fields to the expert and specialist. Standard textbooks often last a lifetime and even though the authors are not at present widely known in this country they may soon be familiar names to future students of meteorology.

The general standard of publication is high and there are comprehensive references at the end of each chapter. Although expensive it is good value at present prices.

A.H.G.

Experiences with the weather. By William M. Bergman III. New York (Vantage Press), 1957. Pp. 371. $3.50.

This book, whose author graduated in science at the University of Delaware and later specialized in Botany at the University of Maryland, comprises a weather record month by month over the twenty-six years 1930-1956. The record, which appears to relate mainly to the author's native place Wilmington, Delaware, about twenty-five miles to the south-west of Philadelphia, is interesting in relation to the effect of the weather on daily life and on the trees, shrubs and flowers of the countryside; and certainly his 'experiences' include many an exciting encounter with blizzards, floods, thunderstorms, tornadoes and hurricanes.

The diary contains many references to contemporary weather at other places near the Atlantic sea-board of the U.S.A., and shows up the sudden drastic changes in winter peculiar to a region lying close to the great St. Lawrence cyclone track between the intense cold of Canada to the north-west and the warm Gulf Stream to the south-east. Thus to quote a case in point, a minimum of 7°F at Wilmington on 13 February 1954 was followed by a maximum on 16 February of 75°.

Summer heat spells in this rather low latitude are naturally severe over a long season and often humid, so that it is not surprising to read that they are rather acutely felt.

L.C.W.B.

Obituary Notice

Mr. ERIC HARVEST

Mr. Eric Harvest died in Toronto, Ontario, Canada, on 10 March 1958 at the age of 26. Born and brought up in Toronto, he graduated in mathematics and physics from the University of Toronto in May 1954 and entered the Meteorological Service of Canada. After receiving his meteorological training he was assigned to the R.C.A.F. station at Cold Lake, Alberta. In the autumn of 1956 he enrolled for the M.A. course in meteorology at the University of Toronto, but ill health prevented him from completing his studies. After some months' convalescence he served on the staff at the R.C.A.F. station Trenton, Ontario, until just before his death. Mr. Harvest was a quiet friendly person with a pleasant co-operative manner. He was elected an Associate Member of the Royal Meteorological Society in November 1956. His keen interest in the physics of weather made him an enthusiastic student and meteorologist.

P.J.

The Falkland Islands Dependencies

Notes on Weather Analysis

By A. W. Mansfield and S. D. Glassey

In January 1950 a forecasting service for local and pelagic whaling factories was started at South Georgia. Weather observations from the bases of the Falkland Islands Dependencies Survey, the Falkland Islands, and South America, together with a small number of ships' observations, formed the basis of the analysis. Apart from a general description of this work, the report deals in more detail with the weather of South Georgia. With 12 text figures.

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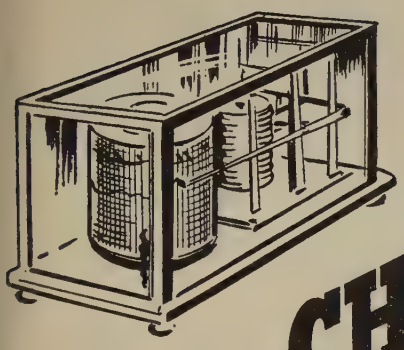

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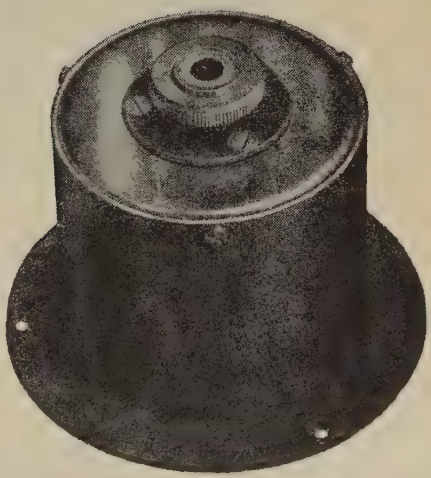

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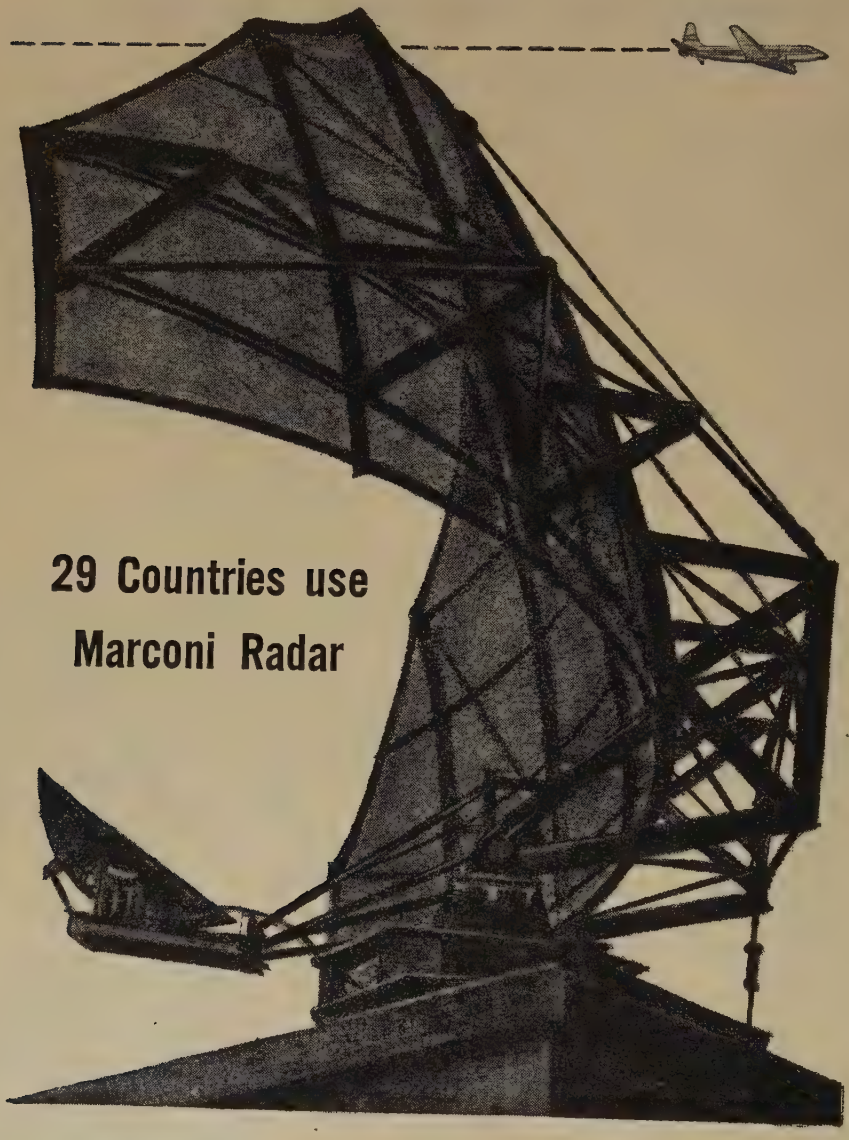

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Canada	Meteorological Division, Department of Transport
Egypt	Meteorological Department
France	Office Météorologue Nationale
Lebanon	Ministère Des Travaux Publics
Mauritius	Royal Alfred Observatory
United Kingdom	Royal Society International Geophysical Year Expedition,
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	Meteorological Office, Air Ministry
Venezuela	Venezuela Air Force—Ministry of Defence

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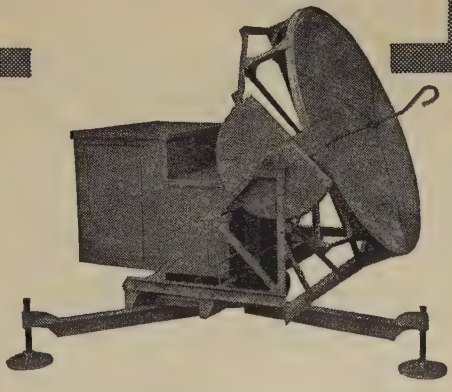

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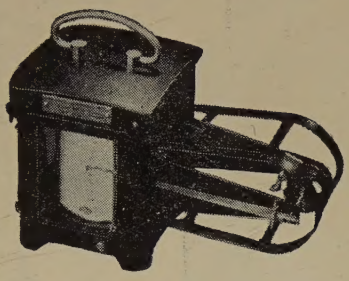

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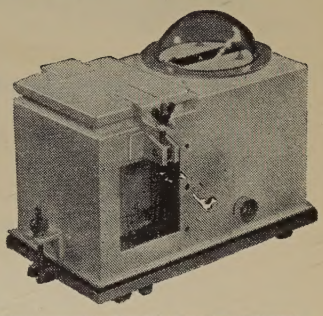

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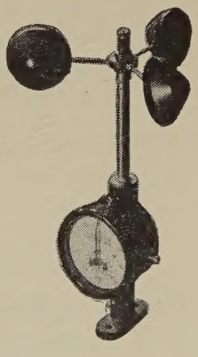

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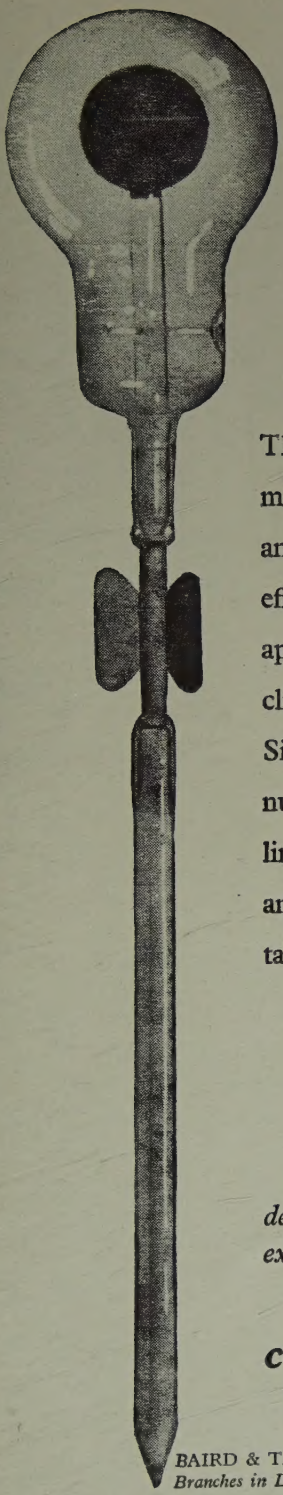

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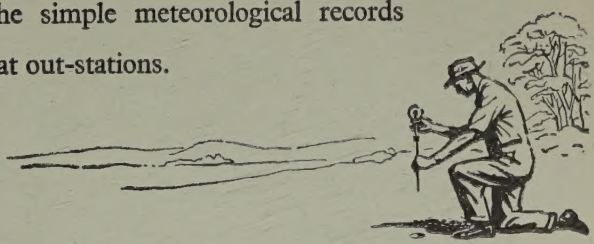

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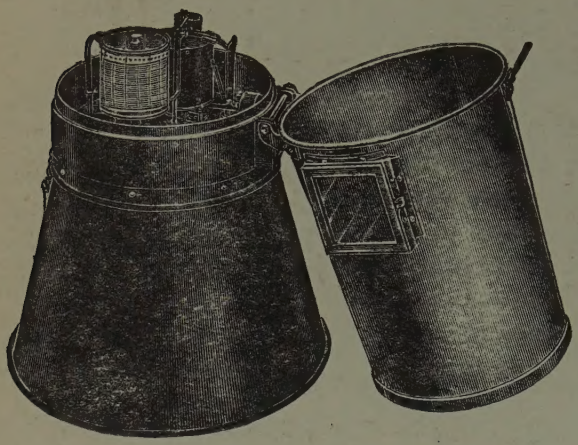

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